Ari Sasmoko Adi, *et.al*

THE ROLE OF THE NATIONAL ROAD NETWORK IN SUPPORTING INTERPROVINCIAL ACCESSIBILITY IN KALIMANTAN

TECHNIUM

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ACCESSIBILITY IN KALIMANTAN

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Foreword

Head of the Regional Research and Innovation Agency of East Kalimantan Province, Indonesia

Praise be to Almighty God for the completion of this book, which carries the important theme of **The Role of The National Road Network in Supporting Interprovincial Accessibility in Kalimantan**. The publication of this work is highly relevant to the current momentum of Indonesia's development, as the establishment of IKN serves as a catalyst for transformation across the entire Kalimantan region. Within this context, the national road network plays not merely a functional role as physical infrastructure, but also as a strategic connector, linking economic, social, environmental, and spatial dimensions in a sustainable manner. This book has been systematically compiled through an interdisciplinary approach that integrates industrial management, regional planning, public policy, road and bridge engineering, environmental engineering, and transportation engineering. Such integration not only enriches the technical understanding of the national road network but also deepens the reflection on Kalimantan's transformation as a unified spatial and economic system within Indonesia's new development framework. The opening chapters introduce the conceptual foundation of connectivity and transformation in Kalimantan, contextualized within the IKN development agenda. The discussion of the strategic role of the national road network, supported by a rigorous research framework and systematic methodology, provides both academic and empirical grounding for the analyses that follow. Subsequent sections elaborate on the fundamental theories of industrial management, regional planning, and infrastructure engineering—key components in shaping effective policies and implementing sustainable national road projects.

Further chapters explore the interconnectedness between technical, economic, and social aspects. Cost, time, and project performance analyses are presented comprehensively, including the application of the CBS, EVM, and sensitivity analysis. These discussions emphasize that infrastructure project management requires a balance between cost efficiency, timely delivery, and quality outcomes, all framed within the principle of sustainable development. In sections devoted to the condition of Kalimantan's road network, the evaluation of the PCI and detailed assessment of pavement quality provide valuable insights into the challenges and maintenance needs of national roads. These findings are then linked to public policy and regional planning strategies aimed at improving accessibility, connectivity, and infrastructure resilience. As a result, the book offers not only technical recommendations but also strategic policy inputs for future infrastructure improvement. Public policy issues receive considerable attention, particularly in the context of data-driven approaches to managing congestion and improving travelability. The book highlights the synergy between government policy and transportation engineering, underscoring the need for evidence-based decision-making to ensure that the development of the national road network aligns with the broader vision of sustainable and inclusive national growth.

Another notable contribution of this book lies in its discussion of the relationship between infrastructure development and agricultural business systems in Kalimantan. Through the analysis of agribusiness corridors and optimization of goods distribution, it demonstrates how the national road network serves as a key enabler for regional economic growth and rural development. This perspective reinforces the idea that infrastructure functions not only as a physical asset but also as a strategic instrument for empowering local economies. Sustainability forms the underlying thread that connects all chapters of this book. The discussion of environmental technology, the use of eco-friendly materials, waste and air pollution management, and the application of green technologies in infrastructure projects reflects an awareness of global environmental challenges and the necessity of low-carbon development. Hence, the book goes beyond the technical dimensions of infrastructure, offering a vision of transformation towards environmentally conscious and future-oriented development.

In its concluding chapters, the book presents an integrated model that links industrial management, regional planning, and transportation engineering for the comprehensive development of Kalimantan's national road network. The holistic evaluation of social, economic, and environmental impacts underscores the importance of cross-sectoral and interdisciplinary collaboration. The final recommendations provide directions for future research, policy strengthening, and enhanced cooperation between government, industry, and communities in achieving inclusive and sustainable infrastructure development. We warmly welcome this book as a meaningful contribution to the academic and policy discourse surrounding Kalimantan's transformation in the IKN era. It is our hope that this publication will serve as a valuable reference for academics, practitioners, and policymakers in understanding the complexity of national road network development and its broader implications for regional transformation. Moreover, we believe it will inspire interdisciplinary collaboration and innovation toward sustainable infrastructure advancement. Finally, I would like to express my sincere appreciation to all authors, researchers, and contributors who dedicated their expertise and effort to this publication. May this collective work serve as a stepping stone toward a more connected, prosperous, and sustainable Kalimantan, representing the new face of Indonesia's future.

Samarinda, December 2025
Dr. M. If. H. Fitriansyah, ST, MM

Preface

All praise and gratitude are due to Almighty God for the completion of this book entitled **The Role of The National Road Network in Supporting Interprovincial Accessibility in Kalimantan**. This book was born out of collective collaboration and shared concern for the challenges and opportunities surrounding the transformation of Kalimantan, particularly as it enters a new era with the establishment of Indonesia's National Capital, which will serve as a new gravitational center for the nation's economy and spatial development. The preparation of this book stems from the belief that infrastructure development—especially the national road network—should not be viewed merely as a physical construction project, but as an integrated system that connects multiple dimensions of development: economic, social, environmental, and spatial. Roads are not only transportation corridors; they are strategic arteries that determine the direction of regional transformation and the prosperity of the communities they serve. This book adopts an interdisciplinary approach, integrating industrial management, regional planning, public policy, civil engineering, transportation systems, and environmental technology. Such integration is intended to provide a holistic perspective on how the development of Kalimantan's national road network can serve as a model for integrated, sustainable, and inclusive regional development. The initial chapters provide a conceptual overview of connectivity and multidimensional transformation within the context of the IKN project. A strong research framework and systematic methodology are presented to analyze the strategic function of the national road network in supporting economic integration across regions. The book also elaborates on foundational theories relevant to industrial management, regional planning, road and bridge engineering, as well as environmental and sustainable technology—establishing a robust academic basis for the subsequent applied analyses. In the following chapters, readers will find comprehensive discussions on the implementation of infrastructure projects, including cost and time management, the application of the Cost Breakdown Structure (CBS) and Earned Value Management (EVM), and the use of sensitivity and trade-off analyses for project acceleration. These topics emphasize the importance of achieving balance between efficiency, timeliness, and quality within the framework of sustainable infrastructure management.

The technical dimension is further elaborated through evaluations of the Pavement Condition Index (PCI) across Kalimantan's national road network, along with in-depth studies of pavement conditions in various regions. These analyses not only illustrate the current state of infrastructure but also propose evidence-based recommendations for technical improvements that are both effective and environmentally responsible. Moreover, the relationship between road conditions, public policy, and regional planning is explored to underscore the importance of cross-sectoral synchronization in achieving optimal development outcomes. Another significant focus of this book lies in the interaction between infrastructure development and agribusiness systems. Through transportation engineering analysis, the authors demonstrate how the national road network enhances the efficiency of agricultural distribution, strengthens agribusiness corridors, and contributes to regional economic growth. This integrated perspective shows that infrastructure development serves not only mobility and logistics needs but also functions as a strategic enabler of local economic resilience and food security. Environmental issues form a continuous thread throughout the book. The discussions on environmentally friendly materials, waste management, pollution control, and green technology applications in infrastructure projects reflect a strong commitment to sustainability and low-carbon development. This aligns with Indonesia's broader vision of environmentally responsible growth and climate resilience, ensuring that progress today does not compromise the needs of future generations. In its later chapters, the book integrates three key pillars—industrial management, regional planning, and transportation engineering—into a unified model for developing Kalimantan's national road system. Holistic evaluations of social, economic, and environmental impacts are presented, followed by strategic recommendations for future research directions, policy design, and strengthened collaboration among government, industry, academia, and communities. We recognize that the preparation of this book is far from perfect; nonetheless, we hope it can offer both theoretical insights and practical contributions for researchers, planners, policymakers, and infrastructure practitioners in Indonesia. Furthermore, we aspire for this work to inspire interdisciplinary collaboration and innovation toward achieving a more connected, competitive, and sustainable Kalimantan. Finally, we extend our sincere appreciation and gratitude to all authors, researchers, and contributors who have dedicated their expertise, time, and effort to the completion of this book. May this work serve as a meaningful contribution to Indonesia's ongoing development—particularly to Kalimantan, as the new face of the nation's future.

Samarinda, December 2025
Authors

Editor

The preparation of this book, **The Role of The National Road Network in Supporting Interprovincial Accessibility in Kalimantan,** represents a collective effort to document, analyze, and interpret one of the most significant spatial and infrastructural transformations in Indonesia's modern history. As the nation embarks on the development of its new capital city, IKN Kalimantan stands at the forefront of change. This transformation is not merely physical; it encompasses economic restructuring, environmental adaptation, and the evolution of governance and regional connectivity. The editors' motivation in compiling this work arises from the recognition that infrastructure, particularly the national road network, plays a central role in shaping regional transformation. Roads are more than physical links connecting cities and districts—they are instruments of social inclusion, enablers of trade, and catalysts for sustainable growth. Therefore, understanding their multidimensional role requires an integrated perspective that bridges technical, economic, environmental, and policy-related disciplines. This book has been designed as a comprehensive and interdisciplinary reference, bringing together insights from diverse fields including industrial management, regional planning, civil and transportation engineering, environmental technology, and public policy. The integration of these perspectives allows the reader to appreciate the complexity of Kalimantan's development landscape, as well as the interdependence between infrastructure systems, spatial planning, and community welfare.

The chapters are organized systematically to guide the reader from theoretical foundations toward applied and policy-oriented analyses. The first sections introduce the conceptual framework of connectivity and transformation in Kalimantan, highlighting the strategic importance of the national road network within the broader context of IKN development. The following sections delve into methodological approaches, analytical models, and interdisciplinary frameworks used to study infrastructure systems in a holistic manner. Subsequent chapters explore the practical dimensions of infrastructure implementation—covering cost and time management, Cost Breakdown Structure (CBS), Earned Value Management (EVM), and sensitivity analyses. These are complemented by empirical studies such as Pavement Condition Index (PCI) assessments and regional analyses of road performance in Kalimantan. Together, they form a foundation for evidence-based recommendations that bridge engineering science with sustainable policy formulation. One of the distinctive features of this book lies in its integration of environmental and socio-economic dimensions. The discussion on environmentally friendly materials, waste and pollution control, and green technologies in infrastructure development reflects a forward-looking commitment to sustainability. Moreover, the exploration of agribusiness corridors and goods distribution optimization underscores the essential link between transportation infrastructure and regional economic resilience. From an editorial perspective, the value of this book lies in its ability to weave together multiple strands of expertise into a coherent narrative. It does not merely present fragmented studies; rather, it offers an integrative framework that can inform future infrastructure planning, research, and policymaking. In doing so, it aligns with Indonesia's long-term vision of creating resilient, connected, and sustainable regions—where development is not confined to urban centers but evenly distributed across the archipelago.

The editors wish to emphasize that the purpose of this book is not only to present research findings, but also to provoke reflection and dialogue. As Kalimantan transitions into a new era of strategic importance, it becomes imperative for stakeholders—from government institutions and industry partners to academics and local communities—to engage in a shared understanding of development that prioritizes both connectivity and sustainability. We hope this book contributes meaningfully to that collective discourse. We express our deepest gratitude to all authors, contributors, and reviewers whose dedication and insights have made this publication possible. Their expertise and interdisciplinary collaboration have given this book its distinctive strength and depth. Appreciation is also extended to the institutions that provided academic and logistical support throughout the research and editorial process. It is our sincere hope that this book will serve as a valuable reference for policymakers, researchers, engineers, and students who are committed to advancing the principles of sustainable infrastructure and regional development. More importantly, we hope it inspires continued collaboration and innovation—ensuring that Kalimantan's transformation in the IKN era becomes a model of integrated and sustainable progress for Indonesia and beyond.

Editor Profiles

Prof. Dr. Bohari Mohd Yamin is a well-known chemist from Malaysia who was born in 1950 in Port Dickson, Negeri Sembilan. With more than four decades of experience, he has made major contributions in the fields of statistics, inorganic chemistry, organographic chemistry, and crystallography, which places him as one of the most influential scientists in the Southeast Asian region. He currently serves as Professor Emeritus at the Faculty of Science and Technology, Universiti Sains Islam Malaysia (USIM).

Prof. Bohari obtained his Ph.D. in Chemistry from King's College London after completing his undergraduate studies at the University of Malaya. His academic career began in 1974 as a tutor at Universiti Kebangsaan Malaysia (UKM), and in 1994 he was appointed as a full professor. During his career, he has served as the Head of the Department of Chemistry, Deputy Dean of the Faculty of Science, and Head of the School of Chemistry and Food Technology at UKM.

As a researcher, Prof. Bohari focuses on the synthesis of organographic compounds, the study of chemical kinetics, and the application of X-ray crystallography. He has published more than 336 scientific papers in reputable international journals, with an H-index of 18 and more than 1,900 citations, reflecting his extensive scientific influence. For his dedication, he received various prestigious awards such as P.J.K., K.M.N., and D.N.S., which recognized his contribution to the development of chemistry.

In addition, Prof. Bohari is active as a keynote speaker and guest lecturer at various international conferences in Asia, Europe, and the Pacific, as well as being involved in academic networks such as SAFEnetwork which strengthens cross-border collaborations between Malaysia, Indonesia, the Philippines, and Thailand. Since his retirement in 2017, he has remained an active role in mentoring young academics through professional training activities and social initiatives to enhance research and publication capacity at regional and international universities. With his dedication and extraordinary achievements, Prof. Dr. Bohari Mohd Yamin became a role model for the next generation of scientists in advancing chemistry and the academic world.

Acknowledgements

All praise and gratitude are extended to Almighty God for the completion of this book, **The Role of The National Road Network in Supporting Interprovincial Accessibility in Kalimantan.** This publication is the result of collaboration, shared ideas, and dedication from many individuals and institutions who have contributed their time, knowledge, and support throughout its preparation and completion.

First and foremost, we would like to express our highest appreciation to the Governor of East Kalimantan Province and the Head of the Regional Research and Innovation Agency (BRIDA) of East Kalimantan Province for their outstanding support, guidance, and commitment to strengthening research and innovation in the region—particularly in relation to sustainable development in East Kalimantan and the establishment of the new National Capital (IKN). Their visionary leadership and encouragement have served as a major source of inspiration for the completion of this book. We also extend our sincere gratitude to our academic colleagues and research partners from various universities, research institutions, and technical agencies who have shared their insights, data, and constructive feedback. Their contributions—through academic discussions, knowledge exchange, and critical reviews—have played a crucial role in enhancing the interdisciplinary foundation that underpins this work. Our deepest thanks also go to the reviewers and technical editors who have carefully examined the manuscript and provided valuable comments and suggestions. Their attention to detail and dedication to academic quality have significantly improved the clarity, consistency, and comprehensiveness of this publication. To the research assistants, data analysts, and technical team members, we express our heartfelt appreciation for their diligence, precision, and teamwork throughout the data collection, processing, and document preparation stages. Their commitment and collaborative spirit were essential in ensuring that the writing and editing process proceeded smoothly and was completed on schedule. We also wish to acknowledge the contribution of various institutions and supporting organizations that provided technical, academic, and logistical assistance during the development of this book. Without their cooperation and shared commitment, the completion and publication of this work would not have been possible. We further acknowledge previous researchers and authors whose studies and findings have provided a valuable foundation for the analyses and concepts presented herein.

Finally, we express our sincere gratitude to our families and loved ones for their constant encouragement, patience, and moral support throughout the research and writing process. Their understanding and faith have been an unfailing source of strength that enabled us to complete this work with dedication and perseverance. We hope this book will serve not only as an academic contribution but also as a practical reference for policymakers, planners, researchers, and the wider community committed to fostering a more connected, innovative, and sustainable Kalimantan. May this work stand as a small but meaningful part of the broader effort to build a prosperous and resilient future for East Kalimantan and Indonesia.

Ari Sasmoko Adi, *et. al*

Contributors

Dr. Ari Sasmoko Adi, holds a Bachelor's degree in Civil Engineering from Lambung Mangkurat University (2000), a Master's in Construction Management from 17 Agustus 1945 University Surabaya (2003), and a Dr. in Forestry from Mulawarman University (2017). A certified expert holding the Certified International Quantitative Researcher (CIQR) credential, he possesses a distinguished portfolio of professional certifications from Indonesia's National Professional Certification Agency, including Ahli Utama (Senior Expert) in Construction Management, Building Engineering, Bridge Engineering, and Water Resources Engineering. He is also certified as a Building Failure Assessor (Ministry of Public Works and Housing), Building Demolition Specialist, and Competency Assessor, in addition to holding a Training of Trainers certification in methodology. His expertise integrates infrastructure engineering, quantitative research, and technical leadership in construction and natural resource management.

Prof. Dr. Drs. Irtanto, M.Si, A Research Professor at the National Research and Innovation Agency, holding the rank of Senior Expert Researcher in Indonesian politics and governance. He was conferred the title of Research Professor with an inaugural lecture entitled Conflict in Regional Autonomy and Its Impact on Government Administration. He earned his Dr. in Public Administration, specializing in public sector bureaucratic performance, from Brawijaya University, Malang. Currently affiliated with the Research and Innovation Agency of East Java Province, he also teaches at the Faculty of Social and Political Sciences of UPN Veteran Jawa Timur and other higher education institutions, and frequently serves as a dissertation examiner across public and private universities. His scholarly output includes several books as well as numerous articles in national and international journals, including the Journal of Southwest Jiaotong University and Webology, covering topics like intergovernmental conflict, bureaucratic performance, elections, local policy, and interregional cooperation. He is an active peer reviewer for several academic journals and has extensive experience leading collaborative research with regional planning agencies and local research bodies. In professional organizations, he served as Chair of the Researcher Evaluation Team and Chair of the Institutional Researcher Assessor Council from 2020 to 2024, was a founding member and executive of the Indonesian Researchers Association in East Java, and currently holds the position of Secretary of the Expert Council of PPI East Java (2022–2025) and Advisory Board Member of HIPIIS.

Prof. Hadi Supraktikta, Holds a Bachelor's degree in Mathematics from Muhammadiyah University of Malang (1992), a Master's in Management Economics from Muhammadiyah University of Jakarta (2001), and a Ph.D. in Public Administration with a concentration in Port Infrastructure Policy (2006). Throughout his career, he has advanced through all levels of the civil service researcher rank achieving the highest rank in 2014. His research output is exceptionally prolific, with hundreds of articles published in international scientific journals, alongside numerous proceedings, books, and registered intellectual property rights stemming from his innovations. Beyond academia, he actively contributes to community service, delivers training, and serves as a keynote speaker at national and international seminars. He mentors graduate students, acts as a peer reviewer for scholarly journals, and plays a key role in professional researcher organizations such as IPINDO and PPI. His career exemplifies a distinguished blend of scholarly excellence, policy-relevant research, and steadfast commitment to human resource development and societal advancement through innovation and collaboration.

Andjar Prasetyo, in the past five years, has conducted research as a regional economics researcher on strategic development issues, including infrastructure planning for economic corridors, the role of Islamic finance instruments in regional competitiveness, and the formulation of provincial science, technology, and innovation master plans. His scholarly output includes 20 peer-reviewed articles published in international journals between 2021 and 2025, addressing themes such as regional economic resilience, green economy adoption, rural credit systems, innovation ecosystems, poverty alleviation, spatial economics, and the socio-economic determinants of public service access. These works—featured in journals such as Heliyon, Sustainability, Frontiers in Public Health, Public Library Quarterly, and IOP Conference Series: Earth and Environmental Science—reflect a consistent focus on evidence-based policy, quantitative analysis, and the interplay between local economic structures and national development strategies.

Sri Setyati is a researcher at The Regional Research and Innovation Agency (BRIDA) of South Kalimantan Province, a position she has held since 2008. Her core areas of expertise include public policy, agricultural policy, health policy, and education policy. In addition to her research role, she has extensive writing and teaching experience as a lecturer at Muhammadiyah University of Jember and IKIP PGRI Jember. She holds a doctoral degree (S3) from Lambung Mangkurat University, a master's degree (S2) from the University of Jember, and a bachelor's degree (S1) from Jenderal Soedirman University.

Prof. Dr. Ir. Husein Avicenna Akil, M.Sc, A researcher with a strong interdisciplinary background in acoustical engineering and social science, holding a Bachelor's degree in Engineering Physics from Institut Teknologi Bandung, Indonesia (1984), a Master's in Applied Acoustics from the University of Salford, UK (1990), and a Dr. in Acoustical Engineering from the University of Liverpool, UK (1996). He was conferred as a Research Professor on April 18, 2012. In recent years, his work has shifted toward socio-economic and policy-oriented research, with a focus on food security, poverty alleviation, agricultural innovation systems, and community resilience. His recent publications appear in international journals such as Evaluation and Program Planning (Elsevier), STI Policy and Management, Uncertain Supply Chain Management, and conference proceedings from IOP and Scitepress. He has also contributed to studies on clove commodity policy, Joint Business Group programs, and innovation platforms for sustainable agriculture. Actively engaged in academic service, he has served as a peer reviewer for multiple national and international journals from 2021 to 2025.

Puput Wahyu Budiman, a researcher and innovation analyst at the Research and Innovation Agency of East Kalimantan Province since 2021, holding a Bachelor's degree in Engineering from Brawijaya University (2010) and a Master's degree in Urban and Regional Planning from Gadjah Mada University (2021), where he graduated cum laude as the top graduate. His research focuses on sustainable urban development, spatial planning, capital city relocation, indigenous settlement patterns, and the socio-ecological dimensions of urban transition in Indonesia. He actively investigates social and environmental issues related to the development of IKN including peri-urban dynamics, greening policies, and the impacts of large-scale urban projects on local communities. His work integrates local wisdom, ecological planning, and spatial justice perspectives into regional development discourse.

Muhammad Setiawan Prabowo, A Research and Engineering Technician at the Regional Research and Development Agency (Balitbangda) of East Kalimantan Province since 2021. He holds a D3 (2011) and D4 (2023) degree in Civil Engineering from Politeknik Negeri Samarinda. With over 12 years of field experience in infrastructure and construction, he has served in various technical roles—including as Junior Group Leader for Site Civil Works (2011), Infrastructure Supervisor (2012–2014), and Handover Coordinator (2015–2020). In his current position, he provides technical support for regional research activities, focusing on civil infrastructure, site assessment, and engineering implementation in development projects across East Kalimantan.

Muhammad Rustam, A senior researcher at the Research Center for Society and Culture, Research Organization for Social Sciences and Humanities, National Research and Innovation Agency, specializing in communication and media studies. His civil service career began in 1985 at the Department of Information, Sidenreng Rappang Regency, followed by assignments at the Center for Press and Public Opinion Research in Makassar (1992) and as Assistant Senior Researcher at the Human Resources Research Agency, Ministry of Communication and Informatics (1997). His research focuses on public communication, media literacy, digital transformation, and information governance. He has led and contributed to numerous studies on online training, public information management, media effects, political communication, and digital behavior across Indonesia—particularly in Sulawesi and Maluku. His scholarly output includes articles in national journals such as Pekommas and Studi Komunikasi dan Media (SKDM), covering topics like internet literacy among civil servants, social media use, rural ICT access, and implementation of the Public Information Disclosure Law. He regularly participates in national scientific forums organized by the Ministry of Communication and Informatics and BRIN.

Noor Wahyuningsih, A researcher at the Research and Innovation Agency of East Kalimantan Province (Balitbangda Prov. Kaltim) since 2011, holding a Bachelor's degree in Mining Engineering from UPN Veteran University Yogyakarta (2008, S.T.) and a Master's degree in Environmental Science from Mulawarman University (2023, M.Ling.). Began professional career in the coal mining industry as a Contractor Management Supervisor (2008–2010) and later as a Junior Mine Planner (2010–2011). Since joining the provincial research agency, has focused on environmental and development issues linked to mining, land use, and sustainability. Has led and participated in key studies on the impact of coal mining on food security, post-mining land utilization, mangrove ecosystem management, clean water availability for the new capital city, and strategies to improve East Kalimantan's Environmental Quality Index. Recent work includes planning Agro-Techno Parks on former mining sites and assessing land-use compatibility in the Sangkulirang-Mangkalihat karst area. Published in national and international journals on mining's economic role, CSR implementation, rural development, eco-innovation among SMEs, and public sector innovation in local government.

Suharsono, A civil servant serving as a Junior Environmental Engineering Researcher, holding a Bachelor's degree in Chemical Engineering from Universitas Islam Indonesia and a Master's in Environmental Science from Universitas Mulawarman. His research focuses on environmental technology and sustainable resource management in East Kalimantan, including rapid site assessment for the Marine Science and Technology Research Center (PUSPITEKLA), development of renewable-energy-based plastic waste distillation systems, patchouli oil processing, fuel oil quality from different plastic types, marine water quality in Bontang, clean water availability for Indonesia's new capital city, and innovation strategies for the fisheries industry. He has also participated in specialized trainings such as Technology Intermediary (Kemenristek, 2013), RISTEK Intermediary Training in Germany (2014), and Management and Quality of Care & Research Training at the University of Adelaide (2023).

Novandi Arisoni, currently serving as a Senior Researcher at the Research Center for Materials, Manufacturing, and Precision Engineering, Research Organization for Engineering and Materials, National Research and Innovation Agency, following a long administrative career at BPPT (1992–2021) in roles spanning planning, cooperation, organization, and state asset management, and subsequent BMN coordination roles during BRIN's transition phase (2022–2023). Holds a Bachelor's degree in Mechanical Engineering from Hasanuddin University (1991) and a Master's in Management from STIE IPWIJA, Jakarta (2007), with extensive training in evaluation methods, quality management, public leadership, and innovation frameworks such as BMC, TRL, Design Thinking, FAST, and SRL—including an international course on photovoltaic business planning in France (2016). Recent research (2024) focuses on industrial cluster development, including dynamic modeling of ethanol clusters, membrane technology for bioethanol SMEs, rubber-modified asphalt business models in South Sumatra, and pineapple commodity cluster profiling in West Java, alongside contributions to the anthology Bunga Rampai Klaster Industri.

Darmawan is a researcher with experience in public policy research, local government, and sustainable development. He completed his Bachelor's degree at STIA LAN (2000), Master of Political Science from Gadjah Mada University (2006), and earned a Doctorate in Government Science from Padjadjaran University (2012). Since 2013, he has been active as a permanent lecturer at Nurdin Hamzah University, Jambi City, teaching various core courses in the Government and Communication Studies Study Program. His empirical research often integrates quantitative approaches and sectoral policies, with a particular interest in regional governance, public service innovation, and cluster-based development in the Southeast Asian region.

Abbreviations

AADT	Average Annual Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
AC	Actual Cost
AEC	ASEAN Economic Community
AEC	ASEAN Economic Community
AHP	Analytic Hierarchy Process
AI	Artificial intelligence
AMDAL	Analisis Mengenai Dampak Lingkungan
ANFIS	Adaptive Neuro-Fuzzy Interface System
ANP	Analytic Network Process
APBN	Anggaran Pendapatan dan Belanja Negara
APCS	Automated pavement condition survey
ASEAN	Association of Southeast Asian Nations
BBPJN	Balai Besar Pelaksanaan Jalan Nasional
BCI	Bridge Condition Index
BIM	Building Information Modeling
BoQ	Bill of Quantity
BPS	Badan Pusat Statistik
BRI	Belt and Road Initiative
BrIM	Bridge Information Modeling
BRT	Bus Rapid Transit
CBA	Cost-benefit analysis
CBR	California Bearing Ratio
CBS	Cost Breakdown Structure
CEEQUAL	Civil Engineering Environmental Quality Assessment and Award for Sustainability
CFD	Computational fluid dynamics
CIM	Civil Integrated Management
CPI	Cost Performance Index
CPM	Critical Path Method
CPS	Critical Path Segments
CSD	Context-sensitive design
CV	Cost Variance
DAF	Department of the Air Force
DEWATS	Decentralized wastewater treatment system
DKI	Daerah Khusus Ibukota

DS	Degree of saturation
EAC	Estimate at Completion
EBPM	Evidence-Based Policy Making
EIA	Environmental Impact Assessment
EMS	Environmental Management System
EPC	Engineering, Procurement, and Construction
EPR	Extended Producer Responsibility
ESAL	Equivalent Single Axle Load
ETC	Estimate to Complete
EV	Earned Value
EVM	Earned Value Management
EVMS	Earned Value Management System
FEM	Finite Element Method
FGD	Focus Group Discussion
FLLAJ	Forum Lalu Lintas dan Angkutan Jalan
FWD	Falling Weight Deflectometer
GDP	Gross Domestic Product
GDP	Gross regional domestic product
GIS	Geographic Information System
GPR	Ground Penetrating Radar
GraPS	Green Public Procurement
GTFS	General Transit Feed Specification
HIM	Holistic Impact Measurement
HMA	Hot Mix Asphalt
HOT	High Occupancy Toll
HOV	High Occupancy Vehicle
HSPK	Hasil Studi Penyusunan Kebijakan
ICT	Information and Communication Technology
IIoT	Industrial Internet of Things
InSAR	Interferometric Synthetic Aperture Radar
IoT	Internet of Things
IRI	International Roughness Index
ISIT	Integrated Spatial Information Technology
ISSCD	Integrated Social, Safety, and Community Development
ITS	Intelligent transport systems
KLHS	Kajian Lingkungan Hidup Strategis
LCA	Life cycle analysis
LCC	Life Cycle Costing
LCCA	Life Cycle Cost Analysis
LHR	Lalu Lintas Harian Rata-rata
LID	Low Impact Development
LiDAR	Light Detection and Ranging

LOS	Level of Service
LRT	Light Rail Transit
MARE	Maritime economic
MBBR	Moving bed biofilm reactors
MCDM	Multi-Criteria Decision Making
ML	Machine learning
MRE	Marine energy
MRF	Material Recovery Facilities
MRLL	Manajemen Rekayasa Lalu Lintas
MRT	Mass Rapid Transit
NBS	Nature-based solutions
NDC	Nationally Determined Contributions
NEOM	New Future City
OAT	One-at-a-Time
PCE	Passenger Car Equivalent
PCI	Pavement Condition Index
PERT	Program Evaluation and Review Technique
PMS	Pavement management system
PPP	Public-Private Partnership
PRIM	Provincial Road Improvement and Maintenance
PUPR	Kementerian Pekerjaan Umum dan Perumahan Rakyat
PV	Planned Value
RAP	Reclaimed asphalt pavement
RD	Rutting Depth
RTRW	Rencana Tata Ruang Wilayah
RUC	Road User Charging
RUJRN	Rencana Umum Jaringan Jalan Nasional
SAGCOT	Southern Agricultural Growth Corridor of Tanzania
SDG	Sustainable Development Goals
SEZ	Special Economic Zones
SHMS	Structural Health Monitoring System
SLCP	Short-lived climate pollutants
SMART	Specific, Measurable, Achievable, Relevant, Time-bound
SPI	Schedule Performance Index
SUDS	Sustainable Urban Drainage System
SUMP	Sustainable urban mobility planning
SV	Schedule Variance
SWMM	Storm Water Management Model
TCO	Total Cost of Ownership
TDM	Traffic Demand Management
TOD	Transit-Oriented Development
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution

UDT	Urban digital twins
UHPC	Ultra-high-performance concrete
US	United States
UV	Ultraviolet
VAC	Variance at Completion
VCR	Volume Capacity Ratio
VOC	Vehicle Operating Cost
VoT	Value of Time
VTT	Value of Travel Time
WBS	Work Breakdown Structure
WinJULEA	Windows-based Java Urban Land-use and Economic Analysis
WMA	Warm Mix Asphalt
WTE	Waste-to-energy
WTP	Willingness to pay

Contents

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CHAPTER 1

INTRODUCTION

Ari Sasmoko Adi | Irtanto

The development of the National Road Network in Kalimantan cannot be separated from Indonesia's national vision to realize equitable development, strengthen regional integration, and structural transformation through the relocation of the National Capital City (IKN) of the archipelago. As the backbone of connectivity in the region that has been shackled by geographical isolation, road infrastructure is present not only as transportation infrastructure, but as a multidimensional lever that touches economic, social, ecological, and geopolitical dimensions at the same time. This document was prepared in response to the complexity of the challenges and opportunities that accompany the acceleration of infrastructure development in Kalimantan, with the aim of providing a holistic analytical framework and strategic recommendations that are holistic, sustainable, and equitable. Through an approach that combines technical innovation, collaborative governance, and respect for indigenous peoples' rights and environmental sustainability, this document is expected to serve as an operational guide for the pema, not just as a physical project, but as a bridge to a productive, inclusive, and sustainable Kalimantan future.

1.1. Kalimantan's Multidimensional Connectivity and Transformation in the IKN Era

Kalimantan, as the third largest island in the world, holds an irreplaceable multifaceted role in Indonesia's national constellation and the global stage. Its strategic position is not only geographical, but also manifested economically, ecologically, and geopolitically. From an economic perspective, Kalimantan is a barn of natural resources that sustains the national economy through the export of major commodities such as coal, petroleum, natural gas, palm oil, and timber. This economic dependence, however, creates an acute development dilemma. On the ecological side, the island is home to one of the three largest tropical rainforests in the world, serving as a crucial carbon sink and global climate regulator, earning it the nickname lungs of the world. The forest is also home to an incredible biodiversity, including endemic and endangered species such as orangutans, proboscis monkeys, and a variety of unique flora. However, this ecological potential is under intense pressure due to massive economic exploitation, which is manifested in the high rate of deforestation, forest and land fires, and peatland degradation. Geopolitically, it is located in the heart of maritime Southeast Asia, directly adjacent to Malaysia and

Brunei Darussalam and facing strategic sea routes, giving it significant bargaining value. Facing the complexity of this challenge—between economic exploitation and ecological conservation, between development lag and strategic potential—an integrated and visionary approach is needed, capable of aligning economic growth with environmental sustainability and social justice, so that Kalimantan's great potential does not become a source of disaster in the future.

The establishment of the IKN of the archipelago in East Kalimantan is a policy maneuver that goes far beyond just moving the center of government administration. This mammoth project can be analyzed as a spectacular urban transformation designed to achieve two main objectives: strengthening the legitimacy of the state and addressing the chronic urban crisis. As analyzed [1], the IKN is an effort to create a new symbolic space—a magnificent stage that represents the vision of a modern, advanced, and environmentally conscious Indonesia, while breaking away from the image of Jakarta that is loaded with colonial heritage and urban issues. Deeper, this relocation can be seen as a spectacular fix, a term that describes how governments are using monumental projects to divert public attention and capital from an unsolvable crisis. In this context, the crisis in question is Jakarta's increasingly critical condition, characterized by severe land subsidy due to excessive groundwater exploitation, crippling traffic jams, air pollution that endangers health, and sharp socio-economic inequality [2]. By carrying a socio-spatial approach, the relocation of IKN to Kalimantan not only aims to redistribute the demographic and infrastructure burden of the island of Java, but is also intended as a catalyst to trigger a domino effect of development. It is hoped that the IKN will become a new epicenter that encourages economic growth, equitable development, and connectivity throughout Kalimantan and the Eastern Region of Indonesia, so as to gradually correct the development inequality that has been very Java-centric. Behind the grand narrative of development and modernization, the acceleration of development in Kalimantan, driven by the IKN project, brings with it social, cultural, and economic dynamics that are very complex and have the potential to cause disruption. The massive migration flow, consisting of state civil servants, construction workers, and economic opportunity seekers from various regions, will inevitably change the demographic and social landscape of East Kalimantan. These rapid social changes, driven by massive urbanization and modernization, have a significant and layered impact on local communities, especially the Dayak, Kutai, and Paser indigenous communities. Their traditional value systems, social norms, and cultural orders face the challenge of erosion due to intensive interaction with immigrant cultures and the demands of the new economy. In the field of education, for example, the system introduced may not adequately accommodate local wisdom, regional languages, or the history of the local community, thus risking alienating the younger generation from its cultural roots [3]. Therefore, the success of the transformation of the IKN cannot be measured by the grandeur of physical infrastructure alone, but must be accompanied by the implementation of policies that are very culturally sensitive and uphold the principles of social justice. In line with the findings on democratic transformation in border areas [4], meaningful participation of local communities in every stage of planning and development, recognition and protection of customary land rights, and ensuring equitable access to economic opportunities and jobs are absolute prerequisites for preventing marginalization, social conflict, and ensuring that development is truly inclusive for all.

Kalimantan's very strategic geopolitical position places it as the vanguard and the main pillar in Indonesia's national resilience architecture. Located in the geographical heart of ASEAN, directly landlocked by Malaysia (in the states of Sabah and Sarawak) and adjacent to Brunei Darussalam, and flanked by strategic waters such as the Makassar Strait, the Sulawesi Sea, and the North Natuna Sea, the island is a barometer of regional stability. The presence of the IKN in Kalimantan dramatically increases the strategic weight of the border area, changing its perception from an isolated "backyard" to a "front porch" of the state that must be guarded and empowered [5]. This strengthening is urgent in light of various cross-border security challenges, such as maritime border disputes in coastal areas between Indonesia and Malaysia (e.g. in the Amalat block), as well as illegal activities such as smuggling of goods, narcotics, human trafficking, and illegal logging. To overcome this, it is necessary to strengthen effective cross-border regulations and collaborative resource governance mechanisms with neighboring countries [6]. Furthermore, maritime governance around Kalimantan is a central issue. Waters such as the Makassar Strait are part of the Indonesian Archipelago Sea Channel (ALKI) II, a vital shipping lane for international trade and global military movements. The sustainability of marine resources and security in these waters must be ensured, demanding increased capacity and presence of the Navy and the Maritime Security Agency (Bakamla) to protect Indonesia's sovereignty and maritime economic interests [7]. In the economic context, the transformation triggered by the IKN opens up a huge corridor of opportunity to re-engineer Kalimantan's economic structure, moving from an extractive economic model that relies on non-renewable natural resources to a more sustainable and knowledge-based economy. The IKN project is expected to be the driving force for the development of the digital economy and the implementation of modern development management [8]. With its status as a new government center designed as a smart and forest city, Kalimantan has the potential to transform into an innovation and investment hub. This vision includes the development of a technology startup ecosystem, the construction of data centers, the application of smart city technology in transportation, energy, and public services, as well as attracting investment in high-value-added sectors. However, the realization of this potential is highly dependent on two fundamental prerequisites: the development of reliable and equitable digital infrastructure, and the strengthening of the capacity of local human resources. The development of high-speed internet networks, such as fiber optics and 5G, should not only be concentrated in the IKN core area, but must be expanded to all corners of Kalimantan to avoid new digital divides. More importantly, there must be massive investment in vocational education and training to equip local communities with skills relevant to the demands of the digital economy, so that they can become key actors, not just spectators, in a new round of development in their homeland.

However, Kalimantan's great potential has historically and systematically been hampered by one of its most fundamental and chronic challenges: the limitations of connectivity infrastructure. For decades, the island's geographical and economic structure forced intercity and interprovincial mobility to rely heavily on two main modes of transportation: river and air. River transport, despite being the lifeblood of inland communities, has a limited range of waterways and is very slow for the movement of goods in large volumes. Meanwhile, air transportation, although fast, has very high costs and minimal carrying capacity, making it an inefficient option for industrial-scale logistics distribution as well as basic needs of the community. The road network that is supposed to be the solution is in a very problematic condition; It is often fragmented, intersected by rivers without adequate bridges, and prone to severe damage. Extreme geographical conditions, such as highly volatile and unstable peatlands and steep hill contours, make the construction of permanent and quality road infrastructure a very expensive and complex engineering challenge. As a result, a landscape of profound isolation has been formed, effectively imprisoning people in the interior and becoming the root of the sharp development disparity between the relatively more developed coastal areas and the isolated and disadvantaged upstream areas. This inadequate infrastructure condition directly leads to high logistics costs, which serve as an invisible tax that burdens the entire economic value chain and suppresses Kalimantan's regional competitiveness. Each stage in the supply chain—from transporting produce from the hinterland to the port, to the distribution of consumer goods from cities to villages—is subject to additional costs due to long travel times, the risk of vehicle damage, and the need for multiple modes of transportation. This condition is in line with the findings of the [9] which explicitly identifies infrastructure limitations as one of the main obstacles that delegitimize the investment climate in Indonesia, especially in resource-rich regions such as Kalimantan. Investors, especially in the manufacturing and value-added industry sectors, are reluctant to invest their capital due to logistics systems that cannot guarantee efficiency, reliability, and cost predictability. In the context of post-pandemic recovery, as emphasized by [10], this challenge is becoming increasingly crucial. The pandemic has exposed the fragility of global and domestic supply chains, so the need for radical infrastructure transformation is no longer just a discourse, but an urgent necessity to build the resilience of national production and distribution systems. This limited physical connectivity extends its impact to the social and cultural realms, creating a significant access gap for people in remote areas. Areas in the interior of Kalimantan, which are often only accessible by days of river travel or pioneer flights with erratic schedules, face isolation from essential public services. Access to quality educational facilities has become very limited, which is reflected in the difficulty of distributing teachers and teaching materials, as well as the high dropout rate. Similarly, access to decent health services, especially for emergency or specialist care, is a luxury that is hard to reach. A study from [11] emphatically shows a direct correlation between the level of physical and digital accessibility and the quality of the human development index in remote areas. Furthermore, in today's digital age, the limitations of physical infrastructure give birth to a new problem: the extreme digital divide. As highlighted by [12], the ambition to transform the digital economy is fundamentally hampered by low internet connectivity penetration and the absence of adequate telecommunications infrastructure. As a result, people in the interior are not only physically isolated, but also digitally, lagging far behind the flow of information, online economic opportunities, and participation in the digital society that are the key to future growth.

This infrastructure inequality occurs not only between Kalimantan and other islands, but also internally within the island itself, deepening the social and economic gap between regions significantly. As emphasized in the [13] discussion, investment allocation and infrastructure development tend to be disproportionately concentrated in established economic centers, such as the Balikpapan-Samarinda corridor, which serves as the main gateway for extractive industries. As a result, other areas—especially those in the interior of Central Kalimantan, West Kalimantan, North Kalimantan, and the eastern part of East Kalimantan—remain lagging behind in terms of access to decent roads, reliable electricity, and quality public services. This phenomenon creates an ironic development paradox: natural resources such as coal, timber, and palm oil are massively exploited from the hinterland, but the economic benefits and state revenues generated from this exploitation are not disproportionately returned to build infrastructure and improve the welfare of local communities who bear the brunt of their environmental and social impacts. This is a reflection of an unexclusive extractive development model, in which wealth flows out of source areas, leaving behind ecological underdevelopment and damage. Efforts to accelerate infrastructure development in Kalimantan, especially those driven by the massive need to support the archipelago's IKN, demand an approach accompanied by technical innovation and policies that are adaptive to unique natural conditions. Given the extreme geographical challenges, conventional construction methods are often ineffective and unsustainable. As emphasized by [14], the science of public administration and responsive governance plays a crucial role in designing development policies that are truly inclusive and sustainable. This includes participatory planning mechanisms involving indigenous peoples, flexible funding schemes for disadvantaged areas, as well as strict oversight to ensure projects run effectively and free from corruption, so that the benefits are truly felt by communities most in need.

Thus, infrastructure development in Kalimantan must be understood not only as a physical construction project, but as a multidimensional transformation project that touches social, economic, and institutional aspects in depth. The construction of roads, bridges, ports, and digital networks is an investment in the "backbone" that will underpin the entire vision of future development. Reliable and equitable connectivity will be the foundation for equitable development efforts, drastically reduce logistics costs to spur industrialization, strengthen the digital economy ecosystem to remote areas, and empower local communities by opening their access to markets, education, and health services. Without fundamental and revolutionary improvements in the infrastructure sector, the great ambition to make Kalimantan the center of modern government, the driving force of Indonesia's new economy, and an example of sustainable development will remain a vision that will be difficult to realize in an inclusive and equitable manner. Therefore, infrastructure transformation in Kalimantan must be placed as the highest national priority that is carried out in an integrated, holistic, and sustainable manner. This demands a strong political commitment embodied through long-term strategic investment allocations, the courage to adopt technological innovations that are appropriate to the local context, and the implementation of participatory and transparent governance models. Only by completely solving the "basic problem" of connectivity that has shackled the island for centuries can Kalimantan's true potential—both as a sustainable lung, a productive resource barn, and as a new center of government that is a symbol of the nation's progress—can be truly unlocked and utilized optimally for the greatest possible benefit of all Indonesian people. Realizing this, the central government is massively investing resources to build and improve the National Road Network, including the monumental Trans-Kalimantan Road project, which stretches from the Indonesia-Malaysia border in West Kalimantan to the eastern tip in East Kalimantan. This infrastructure development is not just a physical project, but a multidimensional strategic intervention that is expected to be able to overhaul the spatial, economic, and social order on this third largest island in the world. In the context of accelerating the development of the IKN of the archipelago, the national road network is the backbone of interprovincial connectivity, connecting economic centers, and supporting national logistics. Therefore, it is crucial to analyze in depth the extent to which the role of this road network is truly effective in improving interprovincial accessibility, promoting regional integration, and accelerating inclusive development amid the complex dynamics that surround it.

Technically, the condition of the main road infrastructure in Kalimantan has shown significant progress. The study [15] shows that most sections of the Trans-Kalimantan Road have been assessed to be in good condition based on the Road Surface Smallness Index (IRI), indicating the readiness of the infrastructure to support inter-regional transportation efficiently. On the economic side, [16] found that road infrastructure is the main mediator between regional budgets and regional economic growth, proving that increased accessibility directly impacts economic activities, such as trade, distribution of goods, and labor absorption. [17] also emphasized that road access is a key factor in developing the potential of tourism and the local economy, especially around the IKN, which is expected to become a new growth center. However, the effectiveness of the national road network in promoting equitable regional integration still faces serious challenges. The analysis of [18] revealed that accessibility is still concentrated at certain points, such as large coastal cities, while inland and interzone areas have not been optimally connected. This creates an exclusive development corridor, where economic benefits accumulate in urban centers, while remote areas remain marginalized. [19] added that the gap between cities and remote areas continues to widen, hindering the full potential of interprovincial integration and deepening development disparities—although in aggregate connectivity has increased.

Furthermore, the construction of this road has an ecological impact that is no less crucial. [20] warn that large infrastructure such as national roads and IKN projects have the potential for broad secondary impacts on ecosystems, especially the fragmentation of wildlife habitats such as orangutans, tigers, and tapirs. Roads that divide primary forests not only threaten biodiversity, but also increase ecological pressures through deforestation, encroachment, and human-animal conflicts. In the context of Kalimantan, which is the lungs of the world, infrastructure development must be balanced between economic needs and sustainable conservation principles, including the implementation of wildlife corridors and ecosystem-based spatial planning. From a technical engineering perspective, the geographical characteristics of Kalimantan—especially peatlands and flood-prone areas—pose a major challenge to the sustainability of road infrastructure. [21] emphasized the importance of geotechnical strengthening and mapping of soil stability to ensure the feasibility of long-term road structures, especially around IKN which are in areas with soft soil and high rainfall. Without an adaptive technical approach, infrastructure is at risk of premature deterioration, incurring high maintenance costs, and failing to deliver sustainable benefits. Meanwhile, social and governance aspects should also not be ignored. [22] show that the perception of social risks towards infrastructure development is greatly influenced by the connectivity of major roads, especially in indigenous peoples and local communities who are worried about the loss of land, culture, and customary rights. Therefore, transparent and participatory communication between the government and local stakeholders is key to the sustainability of the project. Without social legitimacy, even technically sophisticated infrastructure can face social resistance and conflict. However, there is hope from international learning The National Road Network in Kalimantan has great potential as a catalyst for structural transformation, especially in supporting the IKN and encouraging regional integration. However, its effectiveness is measured not only by the length of the road built or the speed of vehicles, but by the extent to which this infrastructure is able to reach remote areas, reduce inequality, maintain ecosystems, and engage local communities fairly. For this reason, a holistic approach is needed that integrates economic, ecological, technical, and social aspects in planning and implementation. Only in this way, roads in Kalimantan will not only become asphalt roads, but bridges to inclusive, sustainable, and equitable development.

1.2. The Strategic Role of the National Road Network in the Transformation of the Kalimantan Region

The writing of this book aims to provide a comprehensive and critical study of the strategic role of the National Road Network in improving interprovincial accessibility on the island of Kalimantan, in the context of the major transformation that is underway in Indonesia, especially with the development of the IKN of the archipelago. In general, this book wants to uncover how road infrastructure functions not only as a transportation route, but as a backbone of regional connectivity capable of accelerating economic, social, and spatial integration throughout the Kalimantan region. In the framework of ambitious national development, national roads are an important element that connects growth centers, border areas, and remote areas, while strengthening the country's legitimacy in realizing equitable development in the frontier areas. More specifically, this paper aims to analyze the existing conditions and development of the National Road Network in five provinces of Kalimantan, including the mapping of the main routes, the functional status of the roads, and their service standards, in order to identify points of disconnection and spatial inequality in the infrastructure network. In addition, this book will evaluate the impact of road construction on improving accessibility, both from a quantitative perspective such as reducing travel time and transportation costs, as well as from a qualitative perspective such as ease of community mobility, access to basic services, and economic integration between regions. This analysis is important to understand the extent to which road infrastructure actually promotes equity or actually widens the gap between coastal and inland areas. Last but not least, the book also aims to identify various challenges that hinder the optimization of road network functions, including technical aspects such as road damage due to unstable peatland and hill conditions, financial aspects such as budget constraints and reliance on complex funding schemes, social aspects such as land acquisition conflicts and indigenous peoples' resistance, as well as environmental aspects such as fragmentation of wildlife habitats and ecological pressures as a result of the opening of access to forest areas. These challenges show that infrastructure development cannot be approached partially, but must be holistic and sustainable. This book will formulate strategic and applicable policy recommendations for all stakeholders—central government, local governments, the private sector, and civil society—to accelerate the realization of a reliable, integrated, and inclusive land transportation system. These recommendations include improving spatial planning, strengthening cross-sector governance, construction technology innovation, and participatory approaches to decision-making. Thus, this book is not only a technical documentation, but also a policy guide that encourages the creation of a connected, fair, and sustainable Kalimantan, where infrastructure development is truly a tool of equity and empowerment for all people.

1.3. Framework for the Study of the National Road Network in Kalimantan

The scope of this book includes an in-depth analysis of the National Road Network as a key pillar in realizing land connectivity on the island of Kalimantan, which is one of the strategic areas in Indonesia's national development agenda. The main focus of this book is on roads with national status, namely infrastructure under the authority of the central government through the Ministry of Public Works and Public Housing (PUPR), because of its central role in connecting cross-provincial areas and supporting economic integration and government. The analysis was conducted comprehensively across five provinces in Kalimantan—West Kalimantan, Central Kalimantan, South Kalimantan, East Kalimantan, and North Kalimantan—with special emphasis on strategic corridors connecting provincial capitals, economic centers, border areas, and areas around the IKN of the archipelago as a new axis of national development. Although the main focus is on national roads, this book also examines the functional linkage between national roads and provincial and district/city road networks that act as feeder systems. This interconnection between road strata is important to ensure that accessibility is not interrupted at endpoints, especially in reaching people in rural and remote areas. Without proper integration between national roads and local roads, the benefits of major infrastructure development risk being enjoyed only by certain urban areas, while the surrounding areas remain isolated.

In terms of time periods, the analysis covers the development of the road network in the last two decades, i.e. from the early 2000s to the present, which is a period of intensification of massive infrastructure investment by the government. This period includes various policy phases, from the expansion of the Trans- Kalimantan Road to the acceleration of development in order to support the IKN. In addition, this book also provides future projections, including strategic road development plans, long-term maintenance challenges, and the need to adapt to the dynamics of economic growth, urbanization, and climate change. Thus, the discussion is not only retrospective, but also prospective, providing an overview of the direction and needs of national road construction in the future.

This book does not discuss in depth other modes of transportation such as river, sea, or air transportation, due to space limitations and analytical focus. However, these modes are still mentioned contextually, especially in understanding their complementary and comparative role in land transportation. For example, in an area that is still heavily dependent on rivers as a major route of mobility, national road conditions are being compared to assess the extent to which mode diversions can occur and how road roads can reduce reliance on expensive and inefficient transportation systems. In addition, the relationship between national roads and access to ports or airports is also discussed as part of the national logistics system. In substance, this book examines various crucial aspects of the national road network, ranging from the planning and implementation process of development, to its impact on the local economy, social mobility, and equitable development. In the economic dimension, it is analyzed how national roads encourage the growth of trade, tourism, and investment activities in previously isolated areas. In the social dimension, its influence on people's access to education, health, and public services is discussed, as well as changes in the pattern of life of the community around the road corridor. Not to forget, the book also highlights the operational and maintenance challenges of roads, especially in areas with extreme geographical conditions such as peatlands, swamps, and flood-prone areas, which require specialized technical and management approaches to keep infrastructure functioning optimally in the long term. The entire analysis in this book is framed in a key context: increasing interprovincial accessibility as the key to regional integration and equitable development. With a comprehensive and integrated approach, this book aims to provide a complete picture of how the National Road Network in Kalimantan is not only a physical infrastructure, but also an instrument of structural transformation that is able to connect regions, strengthen the economy, and realize spatial justice in the heart of the archipelago.

1.4. Integrated Research Methods for National Road Network Analysis

To achieve the goals that have been set, the writing of this book adopts a mixed methods approach, which combines qualitative and quantitative analysis in a balanced manner. A quantitative approach is used to analyze measurable data related to infrastructure and accessibility. This includes the collection and analysis of secondary data from official institutions such as the Central Statistics Agency (BPS) regarding regional demographic and economic data (GDP), the Ministry of PUPR regarding length data and road conditions, and the Ministry of Transportation regarding average daily traffic data (LHR) and logistics costs. In addition, spatial analysis using the Geographic Information System (GIS) will be applied to map the road network, analyze the level of connectivity, and visualize changes in accessibility over time. On the other hand, qualitative approaches are used to deepen understanding of contexts, processes, and impacts that cannot be measured with numbers. The methods used include literature review of government planning documents, research reports, scientific articles, and mass media news. Furthermore, in-depth interviews were conducted with key representative speakers, such as officials from the National Road Implementation Center (BBPJN), academics in the field of transportation and regional planning, logistics business actors, and community representatives who felt the impact of road construction firsthand. The combination of these two approaches allows for analysis that is not only data-robust, but also rich in context and perspective.

1.5. Integration of Disciplines

The study of the role of the road network in supporting accessibility in Kalimantan is a complex and multidimensional issue, so it cannot be adequately analyzed from a single scientific perspective. Therefore, this book builds on the foundation of the integration of several disciplines to provide a holistic understanding. This approach is aligned with a multi-criteria evaluation framework that emphasizes the need for a holistic assessment of infrastructure projects, as proposed [23]. Their multi-sectoral framework for sustainable walking forms the philosophical foundation of this book, which demands that every aspect—from technical to social and environmental—be evaluated in an integrated manner, rather than as a separate entity. The core of the book's analysis comes from Civil Engineering and Transportation Planning Sciences, which provides a framework for understanding the technical aspects of road planning, design, construction, and maintenance, as well as traffic performance analysis. However, these technical screws and bolts do not stand alone. This discipline is fundamentally enriched by Geography, specifically transportation geography and spatial analysis. This perspective is crucial for understanding how the road network interacts with Kalimantan's unique landscape and how it reshapes regional spatial patterns. A study [24] on land-use changes due to economic corridors in Laos provides a relevant mirror for Kalimantan. Their research shows how road construction is drastically triggering spatial transformation, transforming forest and agricultural land into urban and industrial areas. Similarly, an analysis [25] of the Belt and Road Initiative (BRI) project confirms that road infrastructure is the main driver of spatial structure change, which not only connects points A to B, but also creates new economic concentration centers and fundamentally changes urban patterns.

From the perspective of Economics, especially regional economics and development, this book examines the impact of road infrastructure as an artery of growth. Road construction directly contributes to the reduction of logistics costs and opens up market access for isolated areas. This is in line with the findings of [26]) who identified economic corridors as the main catalyst for local economic transformation. Furthermore, on a broader scale, efficient connectivity is a prerequisite for synergies between cities and sustainable regional growth. [27] emphasize the importance of synergy between transportation infrastructure and other public services to drive regional efficiency. In an even larger context, infrastructure projects in Kalimantan can be seen as part of the regional integration agenda in ASEAN, where physical connectivity is a means to improve social and economic cohesion between countries, as discussed [28]. The success of large-scale infrastructure projects depends not only on technical excellence or economic potential, but also on a strong governance framework. This is where Public Policy Science and State Administration provides a critical lens. This discipline analyzes the complexity of decision-making processes, budget allocation, regulations, and, most importantly, coordination between government agencies. This challenge is emphasized [27], who highlight that without collaborative and integrated planning, infrastructure development can actually trigger new problems such as urban sprawl and inefficiency of public services. Therefore, the book analyzes how well-designed policies can maximize the benefits of infrastructure while mitigating their negative impacts.

The integration of Sociology and Environmental Science is the most critical pillar in this analysis, especially considering the context of Kalimantan as a sensitive tropical forest area. Road construction often presents a sharp dilemma between economic development and environmental conservation. An interdisciplinary study [29] in Cambodia provides in-depth insights into this trade-off, where access opening is often followed by deforestation, land degradation, and social conflicts related to land tenure. This phenomenon is not just a local issue, but part of a global trend. [30] identified that waves of large-scale infrastructure development around the world are systematically transforming rural landscapes and challenging social-ecological resilience. As such, the book not only celebrates the economic benefits of the new road, but also critically highlights its social impact on local communities—including lifestyle changes and potential conflicts—as well as its ecological impact on biodiversity. Through this blend of disciplines, the book seeks to present a comprehensive analysis, from technical "screws and bolts" to broader socio-economic and environmental implications. However, the analysis doesn't stop there. The book also looks forward, incorporating discussions on the role of technology and modern sustainability principles. [30] also highlight how digital integration can revolutionize infrastructure planning and management, offering new tools for impact monitoring and network optimization. In addition, sustainability principles applied at the micro scale, such as in mobility initiatives on Southeast Asian campuses analyzed [31], provide inspiration that sustainability mindsets can and should be applied at macro scales such as the construction of regional road networks. Ultimately, by weaving together findings from a variety of case studies from Laos [26], Cambodia [29], to global trends [30] and using a holistic evaluation framework, this book offers a dynamic synthesis. The goal is not only to understand roads as physical structures, but as powerful agents of transformation with profound consequences for Kalimantan's economy, society, and ecosystem.

1.6. Systematics

The book is structured in fourteen interrelated chapters to provide a thorough understanding of the role of the national road network in Kalimantan. After this introduction, Chapter 2 presents a theoretical and conceptual basis that includes industrial management, regional planning, public policy, road and bridge engineering, and environmental engineering. The discussion continued with an in-depth exploration of how transportation techniques support the agricultural business system, given the importance of this sector to the economy of Kalimantan. Chapters 3 to 6 discuss managerial and planning aspects, starting with the role of industrial management in infrastructure development, including cost and time analysis in national road projects. Chapter 4 specifically analyzes the condition of road pavements using the Pavement Condition Index (PCI) and its relationship to public policy. Chapter 5 explores regional planning strategies to support accessibility, with a specific case study on development around the Capital City of the archipelago (IKN). Chapter 6 evaluates public policies in infrastructure management, including the implementation of policies to address congestion based on Volume Capacity Ratio (VCR) and travel speed data.

The technical aspects are discussed in depth in Chapters 7 to 9, which include the principles of road and bridge engineering, environmental engineering, and transportation engineering. Chapter 7 presents a case study of the repair of the Kapuas 1 Twin Bridge in Pontianak as a real example of the application of modern engineering. Chapter 8 analyzes the environmental impact of national road construction and its mitigation strategies, while Chapter 9 focuses on traffic analysis and optimization of goods distribution in Kalimantan. Chapters 10 and 11 explore the linkages between infrastructure and the agricultural sector and the application of environmental technologies. The discussion included how national roads support the distribution of agricultural products and the development of agribusiness corridors, as well as the application of green technology in sustainable development, with the IKN as a pilot model. Chapter 12 presents an economic analysis of transportation through the calculation of Vehicle Operating Costs (BOK) and travel time values, which are important for the evaluation of the feasibility of infrastructure investments. The book closes with Chapter 13 which presents an integrated case study as a real example of the integration of various disciplines in infrastructure development. The holistic evaluation includes the social, economic, and environmental impacts of national road construction in Kalimantan. Chapter 14 as a conclusion presents the main conclusions of each chapter, recommendations for sustainable infrastructure development, suggestions for further research, as well as important messages for stakeholders including government, industry, and society. This systematics is designed to provide a comprehensive and integrated understanding of the complexity of road infrastructure development in Kalimantan.

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CHAPTER 2
THEORETICAL FOUNDATIONS AND CONCEPTS

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The construction of the National Road Network in Kalimantan is a strategic intervention that goes far beyond the physical dimension of construction—it is a multidimensional transformation project that touches on economic, social, ecological, governance, and geopolitical aspects, especially in the context of accelerating the development of the Nusantara Capital City (IKN). As the backbone of connectivity in areas that have been isolated by extreme terrain such as peatlands, hills, and complex river systems, national roads have succeeded in accelerating mobility, lowering logistics costs, and expanding public access to basic services. However, the benefits are still concentrated in coastal corridors, while inland areas—the main source of resource exploitation—are still marginalized, creating an unfair development paradox. The long-term success of this infrastructure depends on the holistic integration of technical innovation, inclusive spatial policies, respect for the rights of indigenous peoples, conservation of tropical rainforest ecosystems, and a geopolitical vision to strengthen ASEAN regional integration. Without a comprehensive and sustainable approach, road construction risks widening inequality, damaging the environment, and triggering social conflict. Instead, if managed with the principles of spatial justice, ecological sustainability, and meaningful participation, Kalimantan's roads can become the foundation of a productive, inclusive, and sustainable new civilization—making Kalimantan not only a barn of resources, but also an example of sustainable development in the world's tropics.

2.1. Basic Concepts of Industrial Management and Regional Planning

Industrial management and regional planning are two disciplines that are symbiotic in the context of regional development, especially in the development of strategic infrastructure such as the national road network. The linkage between the two arises from the need to create an efficient, sustainable, and spatially integrated economic system. Industrial management, in essence, focuses on optimizing production processes, supply chain efficiency, and minimizing logistics costs to increase industrial competitiveness [1], [2]. Within this framework, the road network is not just a physical infrastructure, but a vital artery that connects various nodes of economic activity—from the location of natural resources such as limestone mines or plantations, processing centers such as factories and smelters, to key distribution points such as ports and consumer markets. Logistics efficiency is highly dependent on the quality and connectivity of transportation infrastructure, so industrial management inherently needs the support of regional planning that is responsive to the spatial needs of the industry. On the other hand, regional planning plays a role in allocating space strategically through zoning, land use, and infrastructure development to support economic activities in a directed and sustainable manner. Good planning must be able to anticipate the impact of industrial expansion on the environment and settlements, as happened in the limestone industrial area in Puger, where industrial growth suppresses the quality of residential infrastructure and creates spatial tension between production and settlement functions [3]. It is in this context that the integration between industrial management and regional planning becomes crucial: industrial management provides economic and operational logic, while regional planning provides a spatial and regulatory framework that ensures development runs in a balanced and inclusive manner. Thus, the synergy between these two disciplines not only improves economic efficiency, but also strengthens regional resilience through an integrated approach between production, distribution, and environmental sustainability functions.

To understand the application of integration between industrial management and regional planning in the context of road infrastructure in developed countries, here are some case studies from countries such as Mongolia, Germany, France, and other OECD members. These examples show how a strategic approach to road infrastructure development supports industrial competitiveness and regional development. Table 1 presented illustrates the diversity and complexity of approaches in integrating road infrastructure with regional planning to support industrial activities in various countries, both developed and developing. These practices show that road infrastructure development cannot be viewed solely as a physical project, but rather as a strategic component of a spatial economy that involves cross-sector coordination, economic considerations, and the dynamics of globalization. In Mongolia, for example, the application of multicriteria assessments in transportation route planning demonstrates the importance of scientific and participatory methods to ensure that road routes support industrial logistics efficiency while minimizing social and environmental impacts [4]. A similar approach is seen in Bulgaria, where spatial analysis and network modeling are used to design transport corridors that support local industrial clusters [5]. In OECD countries, further integration is carried out through land value-based fiscal instruments, such as land value capture, which take advantage of the increase in property values due to road construction to finance the infrastructure itself, creating a sustainable financing cycle [6]. Meanwhile, studies from Ukraine and China affirm the role of infrastructure as a lever for regional productivity, where the construction of national roads and freight railways directly increases the accessibility of industrial estates and attracts investment.

Table 2.1. Implementation of Industrial Management and Regional Planning Based on Road Infrastructure

Yes	Country and References	Study Focus	Key Approaches/Findings
1	Bulgaria [7]	National road planning	Economic factors are the main reference in national road development policies
2	China [8]	Integration of rural industries and transport infrastructure	Road infrastructure promotes industrial integration and improves the quality of rural areas
3	China [9]	Regional transportation and industrial efficiency	Road infrastructure supports green productivity in BRI initiative cities
4	China (OECD interface) [10]	Industrial and infrastructure economic zones	China's overseas industrial zone emphasizes infrastructure and supply chain synergy
5	Ethiopia & Argentina [11]	Global industrial and road infrastructure development	Transnational planning and global production networks influence local infrastructure development
6	Global [12]	Global practice of land capture value and road planning	Evaluation of international instruments for regional infrastructure financing
7	Germany/ Argentina [11]	The influence of global industrial networks on regional planning	Development of industrial estates and roads related to global production and transnational actors
8	Kenya [13]	The impact of road infrastructure on regional development	The relationship between road density and regional economic output (although not developed)
9	Mongolia [14]	Regional transport network integration	Use multi-criteria analysis to determine key infrastructure corridors
10	Negara OECD [15]	Land value capture and road policies	Instruments for road infrastructure financing in the context of land added value
11	Southern Africa* [16]	Regional planning and industrial spatial policy	The linkage between spatial planning and the industrial/logistics sector in a macro framework
12	Ukraine [17] [18]	Road infrastructure and tourism access in rural areas	Road transport is important for the planning of rural tourist areas
13		Industrialization and regional community planning	Development of industrial parks as a regional economic planning strategy

Source: Author search, 2025

At the global level, the examples from Ethiopia and Argentina show how transnational actors—such as within the framework of the Belt and Road Initiative (BRI)—influence the design and prioritization of local infrastructure, often leading to the construction of trade corridors connecting industrial estates with export ports [9], [19]. Germany's approach to designing integrated industrial parks with efficient road and rail networks has also become a globally successful cluster-based regional planning model. All of these studies consistently emphasize that the successful integration of road infrastructure and regional planning depends on coordination between government agencies, private sector involvement, and readiness to respond to pressures and opportunities from the global economic system. Thus, road construction is not just a matter of engineering or construction, but is a manifestation of a complex spatial economic development strategy, multidimensional, and involves interaction between local, national, and global actors in creating productive, connected, and resilient regions.

The theory of integration of regional planning and industrial efficiency is a holistic conceptual framework in understanding how economic development can be strategically directed through the synergy between spatial policies and the strengthening of production-logistics systems. This theory explains that economic growth is not just the result of sectoral policies alone, but is a product of planned spatial design, where regional planning provides a spatial and strategic framework to direct growth in an orderly, inclusive, and equitable manner, while industrial efficiency emphasizes on supply chain optimization, minimization of distribution costs, and increased product competitiveness from production nodes to markets or export ports. The roots of this theory can be traced from the growth pole theory put forward by François Perroux, who argued that economic growth does not occur evenly, but rather starts from growth centers that then spread to the surrounding areas through linkage and multiplier effects. This concept then evolved into economic corridor development, where growth is guided by linear infrastructure—such as roads, railways, or pipelines—that connect production centers with consumption and distribution centers. In the context of regional development in regions such as Kalimantan, this theory is concretely realized through the construction of national roads that connect Special Economic Zones (SEZs) with export ports, creating logistics corridors that not only increase industrial efficiency, but also open accessibility to remote areas that are rich in natural resources but have been geographically and economically isolated. The change in spatial structure from a radial pattern to a dumbbell-shaped shape, as occurred in the Laos Economic Corridor [20], shows how infrastructure design can actively reshape economic flows and expand the reach of influence of growth centers. In this framework, regional planning plays a role in determining the direction and boundaries of development through instruments such as the Regional Spatial Plan (RTRW), which identifies growth poles, establishes economic corridors, and determines strategic areas that require priority infrastructure support.

On the other hand, industrial management provides operational logic with an emphasis on logistics efficiency, travel time, and low transportation costs—key factors that determine the industry's competitiveness in the global market. The integration of the two is manifested in a model of spatial functional hierarchy: from industrial estates as production nodes, through logistics corridors as distribution channels, to export ports as gateways to international access. National roads, in this context, function not only as transportation routes, but as the backbone that integrates the regional economic system as a whole. A study of the China-Laos rail shows that the development of transportation infrastructure has a significant impact on spatial transformation, with increased economic activity concentrated within a 2 km radius of the main station [21], proving that infrastructure has the power to reshape spatial structures and create new economic centers. A similar approach is applied in Mongolia, where the determination of the vertical and horizontal axes of the road network is based on multicriteria analysis that takes into account economic, environmental, and social aspects [14], suggesting that infrastructure planning is now increasingly scientific and participatory.

The main goal of this theory is to create an economic spatial structure that is not only logistically efficient, but also socially just and ecologically sustainable. This is especially relevant for underdeveloped or isolated areas such as in eastern Indonesia, where infrastructure development can be a catalyst for economic transformation. One of the main challenges is the potential for land-use conflicts, especially when the acceleration of infrastructure development is not followed by strict regulations, thus triggering uncontrolled conversion of agricultural land or forests, as is the case along the Laos Economic Corridor [22]. In addition, while infrastructure is able to drive growth, its benefits are not always evenly distributed, and can widen the gap between regions if not managed with an inclusive approach. The application of this theory has been proven to be wide, ranging from the preparation of RTRW, SEZ development, logistics corridor planning, to the development of port hinterland areas. An example is the coastal corridor development project in Western Egypt, which integrates logistical, ecological, and spatial considerations of coastal cities in a balanced manner [23].

Conceptually, this theory complements Weber's industrial location theory, which emphasizes the minimization of transportation costs, Wallerstein's world systems theory, which explains the global economic hierarchy, and the concept of global production networks, which shows how local industrial estates are connected in global value chains—as seen in the development of industrial estates in Albania and Ethiopia influenced by foreign investment and development policies. cross-border infrastructure [24]. Thus, the integration of regional planning and industrial efficiency is not only a technocratic approach, but a complex, dynamic, and multidimensional spatial development strategy, which combines economic logic, spatial planning, and the involvement of local, national, and global actors to realize sustainable and equitable development.

2.2. Principles of Public Policy in Infrastructure Development

The development of national road infrastructure in Kalimantan must be understood not solely as a physical construction activity, but as a strategic public policy instrument.

This approach demands a paradigm shift from technical engineering to holistic public governance. Roads are no longer seen as the ultimate destination, but rather as solutions to public problems such as spatial inequality, geographical isolation, and logistical inefficiencies. Thus, the success indicators of the project shift from just the length of the road built to how much the road is able to overcome these structural problems. This perspective is in line with public policy theory, which positions infrastructure development as the state's response to market failures, as well as a manifestation of the state's allocative and distributive functions.

In the framework of modern governance, the principle of equity occupies a leading position. This principle emphasizes that road construction must proactively accommodate disadvantaged, frontier, and outermost (3T) areas, as a form of spatial justice and social inclusion. The application is not to generalize development, but to treat different regions fairly based on their own needs and potential. Empirical validation from [25] shows that an inclusive approach in rural infrastructure prioritization is able to increase the legitimacy of projects and their effectiveness on the ground. The case study of the Parallel Border Road in Kalimantan is a concrete example of this principle: although it is not economically profitable in the short term, it has high strategic value for sovereignty, national integration, and local economic empowerment. The principle of efficiency requires the optimization of public resources to achieve maximum results. However, efficiency in the context of public governance goes beyond just cost saving; It includes optimizing the planning, construction, and maintenance processes. Technology plays an important role here. As revealed [26], the application of satellite imagery, geographic information systems (GIS), and smart sensors (IoT) can speed up the planning process and lower maintenance costs through predictive monitoring. Efficiency also means choosing the right routes, minimizing costly land acquisitions, and avoiding areas at high risk of damage.

However, an efficient project is not necessarily effective. Effectiveness assesses the extent to which infrastructure projects are able to realize broader strategic goals, such as connectivity between regions, reduced logistics costs, and support for new national capitals (IKN). Indicators of effectiveness include reduced travel time, increased trade volume between regions, and economic growth along the corridor. Validation from [27] shows that effectiveness must be measured through outcomes and impacts, not just physical outputs. In the context of Kalimantan, the construction of new national roads will be effective if it is able to create new economic activities and increase spatial integration between provinces.

In addition, in the context of Kalimantan which has high ecological wealth, the principle of sustainability is an important foundation. The roads built should not be a threat to the environment, but instead support their sustainability. The use of KLHS and AMDAL is not a mere administrative procedure, but a tool to guarantee responsible decisions. Mitigation structures such as animal bridges (ecoducts) and track designs that avoid areas of high conservation value are concrete forms of development that consider the carrying capacity of the environment. [28] even emphasized that good road design can shape people's behavior to be more concerned about the environment. Finally, the principle of public participation is the key to social legitimacy and long-term success. Road construction must involve local communities in all stages of the process—from planning to evaluation. Deliberative and collaborative participation not only enriches technical information with local knowledge, but also strengthens the community's sense of ownership of the project. The findings of [29], [30], [31] suggest that projects that actively involve the public have higher success rates, are more resistant to conflict, and are more responsive to local needs that are often not captured by technocratic approaches alone. As a synthesis, the development of the national road network in Kalimantan must be seen as a comprehensive, value-based, and data-driven governance process. The principles of equity, efficiency, effectiveness, sustainability, and public participation are not separate elements, but rather interrelated systems. Failure to implement either can damage the entire system. Therefore, road construction requires not only engineers, but also regional planners, public policy experts, economists, ecologists, and social facilitators. Only with this multidisciplinary and governance-based approach can national roads in Kalimantan become a lever for regional transformation towards a productive, inclusive, and sustainable future.

2.3. Road and Bridge Engineering Theory

Road and bridge engineering theory is an applied discipline in civil engineering that integrates the principles of mechanics, materials, and structural analysis to produce safe, efficient, and sustainable transportation infrastructure. The scope of this theory covers the entire infrastructure life cycle, starting from the conceptual stage, planning, detailed design, construction, operation, maintenance, to decommissioning. In the modern context, this theory not only focuses on structural aspects, but also integrates environmental, socio-economic, and sustainability considerations. This holistic approach considers the complex interactions between structures and their environment, including responses to traffic loads, extreme weather conditions, seismic activity, and climate change. The theory also covers aspects of infrastructure asset management, which involve developing predictive and preventive maintenance strategies to maximize the service life of the structure at optimal cost. The development of road and bridge engineering theory can be traced back to the ancient civilization that built Roman roads and stone bridges, but a significant transformation occurred in the Industrial Revolution era with the discovery of new materials such as cast iron and steel (Fig 2.1.). The post-World War II period marked a new era with the adoption of prestressed concrete and a limit state-based design approach that replaced traditional working stress methods. The 1970s-1980s saw the integration of computers in structural analysis, allowing for more complex and accurate modeling. The contemporary era is characterized by the adoption of Building Information Modeling (BIM) technology, real-time structural sensors, and artificial intelligence for monitoring the health of structures.

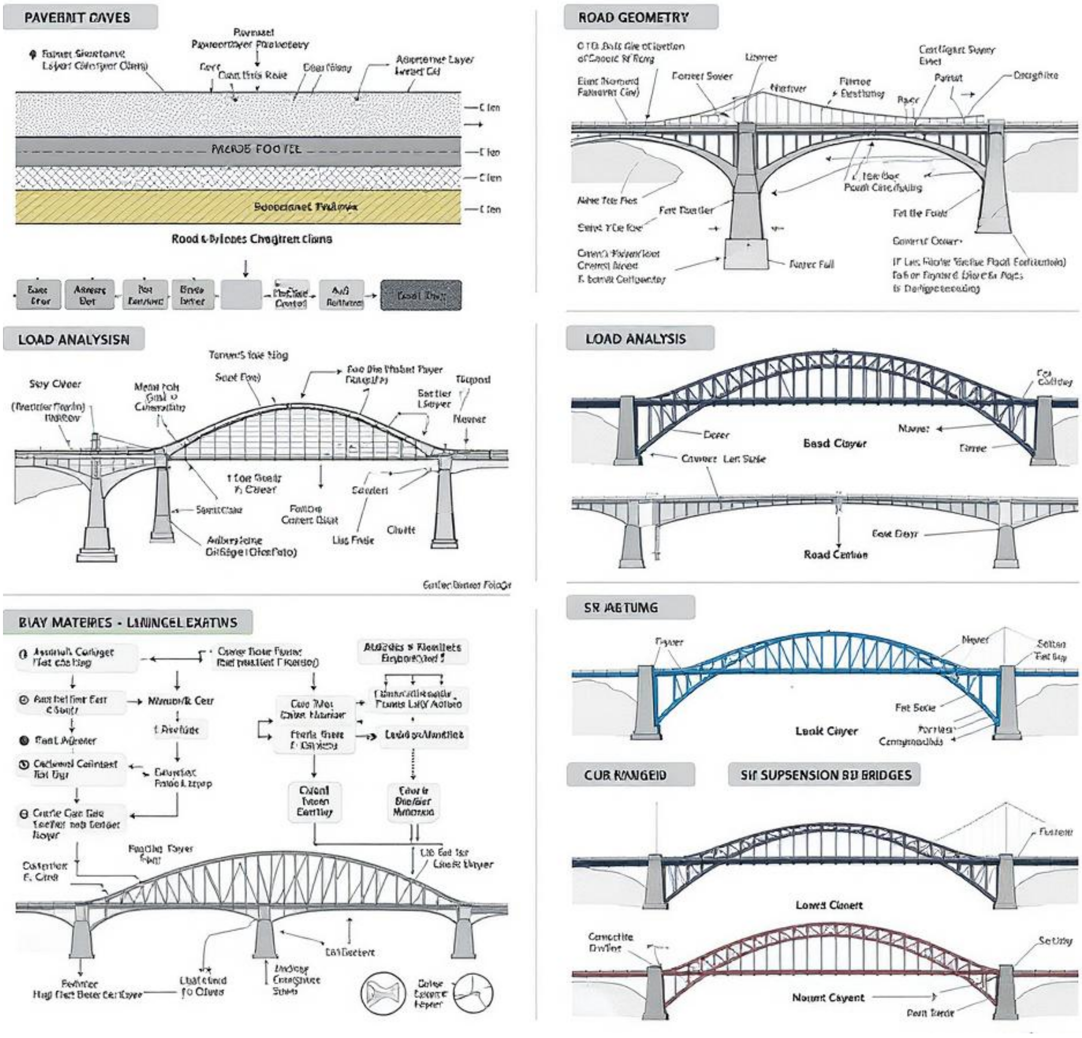

Figure 2.1. Bridge Engineering Model

Source: Author search, 2025

Recent developments also include the use of innovative materials such as carbon fiber composites, ultra-high-performance concrete (UHPC), and self-healing materials that are able to repair micro-cracks automatically. The design paradigm has also shifted from a deterministic to a probabilistic approach, acknowledging the inherent uncertainties in structural loads and responses.

The Dynamic Amplification Factor is a critical parameter that quantifies the amplification of the structural response due to the dynamic nature of the vehicle load compared to the equivalent static load. This concept is fundamental in bridge design because the actual load of the moving vehicle produces a dynamic effect that can significantly exceed the static effect. DAF is affected by a variety of factors including vehicle speed, suspension characteristics, road surface roughness, natural frequency of structure, and damping ratio. Recent research shows that DAF can vary between 1.1 and 1.5 under normal conditions, but can reach much higher values under resonance conditions or when there are significant surface irregularities. An in-depth understanding of DAF allows engineers to optimize structural design, avoiding uneconomical overdesign while ensuring structural safety. Modern DAF evaluation methods use Monte Carlo simulations and spectral analysis to capture stochastic variability in vehicle parameters and operational conditions. The concept of life cycle design represents a holistic paradigm that considers the entire phase of a structure's existence from cradle to grave. This approach integrates Life-Cycle Cost Analysis (LCCA), Life-Cycle Assessment (LCA), and long-term structural performance evaluation. In the context of a bridge, it involves optimizing the trade-off between the initial investment, maintenance costs, durability, and residual value of the structure. Probabilistic models are used to predict material degradation, fatigue damage accumulation, and maintenance intervention needs. This approach also considers externalities such as the cost of traffic disruption during maintenance and the carbon impact of construction activities. Effective implementation of life-cycle design requires a comprehensive database of material performance, validated degradation models, and a multi-criteria decision-making framework that takes into account stakeholder preferences and future uncertainties.

The complex interaction between wind, vehicles, and bridge structures is a critical phenomenon on long span bridges that requires sophisticated aeroelastic analysis. This phenomenon involves a multi-directional energy transfer mechanism where the wind affects not only the structure of the bridge but also the vehicles that cross it, while the movement of vehicles and bridges can modify the local wind flow pattern. This clutch analysis is important to ensure operational safety, especially for tall vehicles such as trucks and buses that are susceptible to lateral wind forces. The mathematical model for this phenomenon involves a system of non-linear coupled differential equations solved using advanced numerical methods. Wind tunnel studies and computational fluid dynamics (CFD) are used to characterize aerodynamic coefficients and identify critical wind speeds that can cause instability. The modern design integrates aerodynamic features such as wind fairings and vortex suppressors to mitigate the detrimental effects of these clutches. The basic assumptions in road and bridge engineering theory form the analytical foundation but also determine the limits of the theory's applicability. Assumptions of material homogeneity and isotropy, while simplifying the analysis, can ignore the inherent variability in actual construction materials. The assumption of linearity in the elastic range facilitates the use of the superposition principle but becomes invalid under extreme load conditions or near-failure. Uniform distributed load assumptions are often used in preliminary analyses but the reality shows significant load concentrations at a given location. The use of partial safety factors in limit state design represents a rational approach to dealing with uncertainty, but calibration of these factors requires an extensive database and consideration of failure consequences. A critical understanding of these assumptions is essential for the proper interpretation of the analysis results and informed design decision-making.

The Element Till method has been a workhorse in bridge structural analysis, allowing for discretization of complex geometries and non-uniform material distribution. The evolution of FEM from static linear analysis to dynamic non-linear analysis has opened up the possibility of simulating increasingly realistic structural behavior. Modern implementations include special elements for modeling the behavior of non-linear materials, contact interfaces, and large deformations. Coupling FEM with other methods such as the Boundary Element Method for soil-structure interaction analysis or the Discrete Element Method for fracture propagation simulation expands the analytical capabilities. Recent developments in high-performance computing allow large-scale probabilistic analysis using Monte Carlo simulation or advanced sampling techniques. Machine learning algorithms are also beginning to be integrated for pattern recognition in simulation results and data-driven design optimization. The risk-based approach in bridge engineering recognizes that absolute failure cannot be completely eliminated, so the focus shifts to rational risk management. Modern risk analysis frameworks integrate hazard assessments, structural vulnerabilities, and consequences. For seismic risk, this involves developing fragility curves that link the intensity of an earthquake to the probability of reaching certain damage states. Multi-hazard analysis considers the interaction between various threats such as a combination of flooding and scouring, or earthquakes and liquefaction. The concept of resilience engineering expands the focus from failure prevention to the ability of systems to recover quickly after an outage. Resilience metrics quantify not only structural robustness but also redundancy, resourcefulness, and rapidity of recovery. The translation of theory into field practice faces a variety of challenges that reflect the complexity of construction realities. Local material variability, especially in developing countries, often deviates significantly from design assumptions. Inconsistent quality of workmanship can introduce unanticipated defects in the theoretical model. Complex geotechnical conditions, including spatial variability in soil properties, challenge simplified assumptions in foundation analysis. Socio-economic factors such as vehicle overloading or unauthorized modifications to the structure create different operational conditions from design intent. Climate change introduces non-stationarity in environmental burdens, challenging traditional assumptions about return periods. Addressing this gap requires an adaptive approach that integrates real-time monitoring, updating field data-based models, and a robust decision-making framework against deep uncertainties.

The implementation of road and bridge engineering theory in strategic infrastructure projects requires customization to local contexts and national objectives. For trans-boundary bridges, geopolitical considerations and harmonization of international standards are critical. Toll road projects require network effects analysis and routing optimization that takes into account future land use changes. Industrial estate connectivity demands a design that accommodates the special loads and high frequencies of heavy vehicles. The value engineering approach is used to optimize the trade-offs between initial cost, performance, and maintainability. Public-private partnership models require a contractual framework that clearly defines performance indicators and risk allocation. Integration with multimodal transportation systems and smart city infrastructure is becoming increasingly important in the context of rapid urbanization. The theory of road and bridge engineering does not exist in a vacuum but interacts synergistically with various related disciplines. Integration with structural mechanics theory provides an analytical foundation for the prediction of structural responses. Transport theory provides operational context and demand forecasting that informs design capacity. Geotechnical engineering provides an understanding of soil-structure interactions that are critical to foundation design. Environmental engineering contributes to ecological impact assessment and mitigation strategies. Urban planning perspectives ensure that infrastructure is harmoniously integrated with the urban fabric. Materials science advances open up possibilities for innovative solutions. This synergy is facilitated through integrated project delivery methods and collaborative platforms that allow real-time information sharing between disciplines.

The future of road and bridge engineering theory will be shaped by the convergence of disruptive technologies and the imperative of global sustainability. Digital twins that integrate real-time sensor data with physics-based models will enable predictive maintenance and performance optimization. Autonomous vehicles will change loading patterns and open up possibilities for more efficient infrastructure designs. Advanced materials such as self-sensing concrete and shape memory alloys will enable smart structures that can adapt to loading conditions. Circular economy principles will encourage design for disassembly and material reuse. Climate adaptation will require an infrastructure that is resilient to extreme events that are increasingly frequent and intense. Quantum computing could revolutionize simulation capabilities for ultra-complex systems. This development requires continuous evolution in theoretical frameworks and educational curricula to prepare the next generation of engineers. Road and bridge engineering theory provides a technical and scientific foundation for designing and building safe, durable, and functional transportation infrastructure. The discipline covers several crucial domains that are highly relevant to topographic and geological challenges in Borneo. Road geometric design is the main foundation, which discusses the determination of horizontal alignment (curves), vertical alignment (slopes and descents), and cross-section of the road to ensure the safety and comfort of the rider at the planned speed. Road geometric design theory is a branch of transportation engineering that regulates the technical principles of determining the physical shape of roads—including horizontal alignments, vertical alignments, and cross-sections—with the primary goal of creating a safe, efficient, and comfortable road system for users at a specified planned pace. This theory is the basis for designing road infrastructure that can adapt to terrain conditions and diverse mobility needs. This theory developed since the early 20th century with the increasing use of motor vehicles and the need for a more structured road system. Originally developed by institutions such as AASHTO and the Indian Roads Congress, the principles of geometric design continue to evolve with the entry of technologies such as GIS, UAVs, and digital optimization algorithms. This condition is reflected in the study by Said et al. (2024) who used the Fault Tree Analysis method to choose the best route in rugged terrain such as the Golden Triangle, Egypt, taking into account more than 14 design factors [32]. Important components of this theory include: horizontal alignment (the minimum bend and radius for the vehicle to avoid slipping), vertical alignment (slopes and descents that are appropriate to the vehicle's acceleration and deceleration capabilities), and cross-sectional (path width, shoulder, and slope for drainage). In addition, superelevation is also used to balance the centrifugal force on the corner, while minimum visibility is used to determine safe stopping distances in various road conditions [33].

This theory assumes that the driver will behave in accordance with the vehicle's operating standards; that the road surface has friction characteristics that comply with the standards; and that environmental conditions such as weather and visibility remain within the limits considered in the design. Thus, geometric design is often done in the context of idealizing real conditions. This theory works in an input–process–output system. Inputs include plan speed, topography, and traffic volume data. The process is technical calculations such as bend angle, superelevation, and slope slope, while the output is a complete geometric design. Technologies such as the InSAR method are used to detect road slope deformation [34], and UAVs are used for avalanche analysis as conducted [35].

The aim of this theory is to ensure that the road design is able to support mobility that is safe, efficient, and in accordance with the characteristics of the vehicle as well as the local geographical conditions. In Borneo, with its hilly areas and swampy areas, this theory is key to reducing the risk of accidents and maintaining long-term road operational viability, as evidenced in an analysis of flood slopes by [36] in Guizhou, China . The main advantage of this theory is its ability to provide measurable and structured guidelines that can be applied widely, even in extreme terrain. However, the weakness is an idealistic approach that is sometimes not sufficiently responsive to environmental dynamics in the field. The study of [37] shows how mining activities can affect the geometric stability of roads in Serbia, requiring advanced soil deformation modeling for anticipation. This theory is widely applied in the design of national roads, toll roads, and border roads. In Indonesia, for example, geometric design is used to design the road to the IKN area in Kalimantan by paying attention to slope, visual safety, and drainage. A study [38] proposed a Laplace transform to calculate vertical deformation in the road-bridge transition zone as part of the application of this theory. The theory of road geometric design complements the theory of traffic engineering (in the context of driver capacity and behavior), the theory of soil mechanics (in the stability of slopes and foundations), and the theory of sustainable transportation (in the influence of design on emissions and energy consumption). This integration is essential in the development of modern infrastructure that is not only reliable, but also adaptive and sustainable.

In Kalimantan, which has contours that vary from lowlands to hills, the application of proper geometric design is key to avoiding accident-prone points. Furthermore, pavement engineering is very vital considering the condition of the subgrade soil in Kalimantan which is dominated by soft soil and peat with low bearing capacity. This theory includes the analysis of materials (aggregate, asphalt, concrete), the design of the thickness of the pavement layer, and the selection of the type of pavement (flexible/rigid) that is able to withstand heavy traffic loads—especially from mining and plantation transportation—and withstand climatic conditions with high rainfall. Pavement engineering is a branch of civil engineering that studies the structure of road pavement to efficiently distribute traffic load to subgrade soil, maintain road functional performance, and extend the service life of transportation infrastructure. The essence of this theory lies in the selection of the type of pavement—both flexible pavement and rigid pavement—and the thick design of each layer of pavement based on traffic conditions, mechanical properties of the material, and environmental factors such as high rainfall and soil moisture. This theory has evolved since the early 20th century, starting with empirical approaches such as the CBR method, and then evolving into the mechanistic-empirical (M-E) approach, which is now a common practice in modern pavement design. [39] explain that this transition is triggered by the need to adapt design to variations in subgrade conditions, climate, and traffic volumes more precisely. In practice, this theory relies on layered analysis, in which the vehicle's load is spread downwards through the surface layer, the base layer, and the subbase, before reaching the base soil. The main concepts of this theory include material characteristics such as modulus of elasticity, compressive strength, thermal stability, and resistance to plastic deformation. In the context of water-saturated ground soils such as in Kalimantan, [40] show that saturation levels greatly affect the resilient modulus of unbound granular materials, which ultimately affects the durability of road structures to heavy loads from transporting mining and plantation products. The basic assumptions of this theory include the homogeneous properties of the layers, the elastic or plastic behavior of the material depending on the approach method, and the linear load distribution model in the initial design.

Modern pavement models are typically analyzed with software such as KenPave, BISAR, and WinJULEA, as was done [41] in the development of StormPav—a type of eco-friendly pavement—which shows better performance under conditions of repeated loads and urban flooding. The main goal of this theory is to design a road structure capable of accommodating long-term dynamic loads, minimizing surface deformation, and maintaining functionality even in the face of extreme climates. The relevance of this theory is increasingly evident in wet tropical regions such as Borneo. For example, [42] evaluated the pavement structure on highly expansive black cotton soil in Nairobi, Kenya, and concluded that the pavement deformation response varies greatly between dry and wet seasons, which demands adaptation of thickness and layer type. The strength of this theory is its ability to answer design challenges across climate and traffic conditions, but its weakness lies in its reliance on often incomplete field data. [43] asserts that the M-E method although more accurate, still requires local calibration and additional testing for design consistency. The applications of this theory are wide, from the design of national roads and toll roads to drainage pavements in cities with a risk of inundation. [44] showed that the combination of permeable pavement layers can reduce water runoff and increase road carrying capacity in areas with heavy rainfall, such as in northern China. In the context of sustainability, pavement engineering is also connected to a green geotechnical approach, as discussed in [45] by Springer, with the utilization of geosynthetics and industrial waste to strengthen subsoils and reduce carbon emissions from road construction. To cope with the landscape separated by many large rivers, bridge structural engineering plays a central role. This theory includes load analysis (dead load, live load, earthquake load, wind load), selection of structural system (girder, frame, hanging), and solid foundation design to ensure the stability of the bridge in the long term. The overall application of this theory must be integrated with hydrological and drainage analysis to effectively manage surface water flow, preventing inundation and erosion that can damage road and bridge structures. Bridge structural engineering theory is a branch of civil engineering that studies the design, analysis, and construction of bridge structures by considering various workloads such as dead loads, live loads, earthquake loads, and wind loads. The essence of this theory is to maintain the stability, strength, and durability of the bridge throughout the service life of the infrastructure.

This theory began to develop systematically since the industrial revolution when the need to unite regions with geographical barriers such as rivers and valleys increased. As materials technology (such as steel and reinforced concrete) and structural analysis methods develop, bridge engineering approaches have become more complex and precise. A study by [46] used the Analytical Hierarchy Process (AHP) method to evaluate the structural condition of the bridge based on eight indicators, including load, hydrology, geotechnical, and traffic. Key components in this theory include load analysis, the selection of structural systems (girders, curves, hangings), foundation design (deep or shallow), as well as the influence of hydrology and drainage. The choice of system depends on the length of the span, soil conditions, and aesthetic needs. For the influence of water, hydrological analysis is important, as explained [47] in a study of drainage system rehabilitation in Tehran to avoid structural failures due to waterlogging. This theory assumes that all loads can be modeled deterministically or probabilistically, and that materials behave in linear or plastic elasticity depending on the analytical approach used. In addition, it is assumed that hydrological data such as planned flood discharge are available to analyze the foundation and elevation design of the bridge. The structure theory is based on finite element methods and 2D and 3D analytical models to design axial loads, bending, and torque on structural elements. In the context of hydrology, models such as SWMM and HEC-RAS are used to model water flow and drainage design around bridges. [48] applied HYKAS and GraPS to assess the capacity of drainage channels in Pokhara, Nepal, and concluded that most channels do not adequately handle runoff discharge. The goal of this theory is to ensure that the bridge structure is safe against all types of possible loads, both static and dynamic, and is able to withstand extreme conditions such as floods, earthquakes, and erosion. In the context of Kalimantan, which has large rivers and swampy soils, the relevance of this theory is very high for designing bridges that are not only sturdy but also adaptive to climate change and seasonal flooding, as shown in the simulation of the flooding of the Jijan River in Malaysia [49]. The main advantages of this theory are the precision of load calculation and multidisciplinary integration with geotechnical and hydrology. However, the disadvantages lie in the complexity of the data and the high reliance on input assumptions (e.g., long-term hydrological data), as well as the high cost of advanced analysis and simulation. This theory is applied in the design of bridges on toll roads, large river crossings, and urban flyovers. In many countries, the evaluation of bridge condition is carried out with an index system such as the Bridge Condition Index (BCI), which combines an assessment of structure, load, and flood risk. [46] compiled this system for five bridges in Iran, which can be a reference for similar implementations in Borneo. Bridge structural engineering theory is closely integrated with geotechnical theory (for foundations), fluid flow theory and hydrology (for flood prediction and drainage design), and infrastructure management theory (for maintenance and condition evaluation). This integration is important so that the design is not only strong in terms of structure but also resilient to environmental and social dynamics. Therefore, the success of the national road network in Borneo in supporting accessibility depends heavily on the ability of engineers to translate these engineering theories into innovative design solutions that are adaptive to the unique characteristics of the island.

2.4. Fundamentals of Environmental Engineering and Environmental Technology

Large-scale infrastructure development such as the national road network in Kalimantan, known as one of the world's lungs with high biodiversity, inherently deals with environmental issues. The role of the fundamentals of environmental engineering and environmental technology in road infrastructure development is becoming increasingly strategic amid increasing pressure on ecosystems and public health due to the expansion of major construction projects. Environmental engineering, as the application of the principles of science and engineering to protect and improve the quality of the environment and human health, occupies a central position in ensuring that road construction is not only economically efficient, but also ecologically sustainable. In the context of road construction, the main focus is on mitigating negative impacts through preventive (early prevention) and curative (post-damage repair) approaches, with Environmental Impact Analysis (EIA) as a key instrument. An EIA is a mandatory scientific study that aims to predict, evaluate, and formulate management measures for the critical impacts of a project, including potential deforestation, fragmentation of wildlife habitats (such as orangutans, elephants, and other endemic animals), soil erosion, river sedimentation, and air and noise pollution during and after construction. A study [50] confirms the importance of a transparent EIA process that involves public participation, especially in road projects that traverse forest areas, to ensure social accountability and ecological sustainability.

To address the challenges identified in the EIA, environmental technologies offer concrete and innovative solutions that are increasingly sophisticated. One of the classic issues in road construction is habitat fragmentation, which threatens the sustainability of wildlife populations. In this context, the application of ecological principles through the construction of wildlife crossings such as flyovers, underpasses, or special culverts has been proven effective in maintaining the connectivity of animal corridors. [51] showed that wildlife crossing designs that take into account migratory behavior and local species preferences are able to reduce animal deaths due to vehicle collisions and restore ecosystem function, while [52] study proves the effectiveness of such structures in improving animal mobility in fragmented areas. On the other hand, soil erosion and sedimentation—the common impacts of road construction in forest and hill areas—can be controlled through bioengineering and vegetation approaches. [53] show that the use of local vegetation such as vetiver, ground-retaining grasses, and live staking systems is not only effective in stabilizing slopes, but also increasing biodiversity and restoration of degraded ecosystems. A similar approach was confirmed [54], who found that forest roads built without vegetative mitigation contribute significantly to river erosion and sedimentation, while [55] used satellite imagery to model changes in soil moisture and post-construction erosion, paving the way for high-tech based monitoring. Other challenges such as air pollution and noise during construction are also addressed through technological innovation. [56] examines PM10 emissions from road construction activities and offers a mitigation model based on wetting of work areas, the use of dust suppressants, and material closure. Meanwhile, [57] introduced intelligent measurement technology to monitor and reduce noise pollution from construction machinery in real-time, enabling operational adjustments to minimize the impact of noise on surrounding communities. [58] compiled a comprehensive review of noise pollution mitigation strategies from construction and transportation, emphasizing the need for a multidimensional approach that combines technology, regulation, and design. In a broader dimension, green construction technology is an integral part of the sustainability paradigm. [59] shows that the use of eco-friendly materials such as recycled aggregates, hot mix asphalt, and sustainable steel can reduce carbon footprint and energy consumption, while [60] review various green technology strategies in road construction that support long-term sustainability. To ensure sustainability throughout the project lifecycle, the Life Cycle Assessment (LCA) approach is increasingly adopted as a scientific evaluation tool. [61] introduced a new approach to LCA for road projects that includes impacts from the material extraction stage to decommissioning. A similar study [62] evaluated the environmental footprint of key construction materials such as asphalt, cement, and steel, finding that the use of recycled materials and energy-efficiency technologies can reduce emissions by up to 30–50%. A multicriteria approach as proposed [63] also enriches the decision-making process by simultaneously considering ecological, social, and economic aspects in hill road projects.

Thus, the integration of environmental engineering and environmental technology is no longer adjunctive, but rather the core of the planning and implementation of modern road infrastructure. From the planning stage (EIA), design (wildlife crossing, bioengineering), construction (green technology, pollution control), to operation and monitoring (LCA, satellite imagery, intelligent sensors), this approach guarantees that road construction not only meets mobility needs, but also maintains ecological balance, protects public health, and meets the principles of sustainable development. In the context of national road construction in Kalimantan or other tropical forest areas, this approach is a necessity to prevent irreparable environmental degradation. In addition, the application of environmentally friendly construction technologies, such as the use of recycled materials or locally processed materials that are processed sustainably, is also part of this paradigm. Thus, the integration of environmental engineering and technology in every stage of the project cycle—from road trajectory planning to operation—is an absolute prerequisite for ensuring that increased accessibility in Kalimantan is not compensated for by irreversible ecological damage.

2.5. Interdisciplinary Relations: How Transportation Engineering Supports Agricultural Business Systems

The relationship between transportation techniques and agricultural business systems (agribusiness) is a fundamental symbiotic relationship of mutualism, where the success of one party is highly dependent on the efficiency and availability of the other—especially in agrarian regions such as Kalimantan, which is rich in food commodities, plantations, and forests, but often faces accessibility challenges. The agricultural business system is not just a production process on agricultural land, but a complex value chain that includes pre-production (provision of seeds, fertilizers, and tools), production (cultivation), post-harvest (collection, sorting, storage), processing, to marketing and distribution. Each link in this system is particularly vulnerable to logistical bottlenecks, especially if the transportation infrastructure is inadequate. It is in this context that transportation engineering plays a key catalyst for agribusiness growth. A network of roads technically designed by transportation engineers—taking into account load capacity, drainage, soil conditions, and seasonal accessibility—is able to cut travel times, reduce crop damage, and drastically reduce logistics costs, thereby increasing the competitiveness of agricultural products in both local and global markets. The importance of transportation networks in maintaining the resilience of agrifood systems has been emphasized [64], which states that a robust transportation system is the main support for food security, especially when disruptions such as natural disasters, conflicts, or global crises occur. In Brazil, for example, [65] points out that poor transportation infrastructure causes logistics costs to reach up to

40% of the value of agricultural products such as soybeans and corn, thus directly eroding export competitiveness. A similar phenomenon can occur in Kalimantan if national road construction is not strategically integrated with agribusiness needs. [66] shows that multizone optimization algorithms are able to improve cost, time, and emission efficiency in the distribution of agricultural products in rural areas, proving that transportation engineering innovation is not only about physical infrastructure, but also intelligent goods movement management systems.

Furthermore, transportation techniques also strengthen rural development and smallholder empowerment through integration with logistics centers. [67] found that logistics distribution centers connected to a good road network are able to help smallholders enter more competitive and efficient agro-food supply chains, reduce dependence on intermediaries and increase profit margins. This is in line with the concept proposed [68], that the development of logistics chains in agribusiness is not only a technical response, but also a market reaction to create added value and drive the transformation of rural economies. In the midst of global crises such as wars or logistical disruptions, such as those in Eastern Europe, [69] notes that small producers are forced to turn to value-added products (such as local processing) to reduce their dependence on expensive and unstable distribution networks an adaptation that is only possible if transportation and logistics infrastructure supports local processing and distribution processes. From an economic perspective, the quality of transportation infrastructure has become a comparative advantage in a sector that relies heavily on logistics, including agribusiness. [70] shows that countries with reliable transportation and logistics systems have a stronger bargaining position in global trade. The choice of mode of transportation—road, train, river, or sea—also strongly determines the efficiency of the export distribution of agricultural products, as analyzed [71], who emphasizes the importance of synergy between modes and the availability of supporting infrastructure such as crossing ports or agro terminals. In the Borneo region, which has an extensive river system but a limited road network, the integration of land and water transportation is key to reaching the centers of agricultural production in the interior. In addition, [72] emphasize that the provision of agrarian infrastructure—including village roads, warehouses, and digital access—not only supports global food security, but also enables synergies between actors, such as farmers, processors, and distributors, in an integrated logistics ecosystem.

For farmers, the development of quality road infrastructure not only means easier and cheaper access to agricultural inputs such as seeds, fertilizers, and agricultural tools, but the most significant impact is felt in the post-harvest phase—the most vulnerable to losses in the agricultural value chain. For perishable commodities such as fruits, vegetables, and other horticultural products, reducing travel time from land to market, collection centers, or processing plants is a determining factor in minimizing the rate of damage or post-harvest losses. Poor road infrastructure, as it occurs in many rural areas in developing countries, causes transportation to be slow, inconvenient, and often damages products due to excessive shock. Studies in Bangladesh show that post-harvest pineapple spoilage is strongly influenced by inadequate transportation systems as well as lack of adequate storage and packaging facilities [73]. In Nigeria, research [74] proves that increasing rural road access directly increases agricultural productivity, reduces post-harvest losses, and increases farmers' incomes. Similar findings have also emerged from Afghanistan, where poor road systems have led to distribution delays and physical damage to apples, resulting in huge losses for farmers [75]. The problem is even more complex when cold storage facilities are not available along transportation routes. [76] note that in many areas, poor road infrastructure combined with the absence of cold chains leads to rapid spoilage of commodities such as vegetables and fruits. This condition is exacerbated during crises such as the pandemic, when distribution disruptions become more frequent and farmers in rural areas lose crops due to a lack of temporary storage or processing [77]. Poor post-harvest handling, including the use of unsuitable modes of transportation, directly leads to a decline in product quality in a short period of time, as revealed [78] in the context of vegetable distribution in mountainous regions.

However, technology and logistics solutions are starting to offer hope. Agri-tech interventions such as solar-based cold storage and digital platforms have been shown to lower crop damage rates and increase farmers' connectivity to the market, especially in hard-to-reach hilly areas [79]. Innovations such as solar-powered mobile cold chains integrated with electric vehicles show great potential in reducing microbiological damage and weight loss of agricultural products during transportation [80]. Meanwhile, [81] show that the design of a distribution network that uses a fast and efficient transportation fleet can increase farmers' profits while reducing product quality degradation in long-distance delivery. Furthermore, quality roads not only speed up distribution, but also open up wider market access for products from previously isolated hinterland. [82] emphasize that increased market access and value chain integration are strongly influenced by distance to market, transportation costs, and crop loss rates—factors that can be remedied through road construction and evidence-based logistics strategies. In the context of Kalimantan, for example, a national road network connected to export ports allows superior commodities such as palm oil, rubber, and forest products not only to reach the domestic market, but also to enter the global value chain. Thus, road infrastructure is not just a physical pathway, but an economic artery that connects farmers to opportunities, reduces losses, increases incomes, and ultimately strengthens regional food security. The integration of reliable roads, post-harvest technology, and efficient logistics systems is key to the transformation from subsistence to inclusive and sustainable modern agriculture.

Transportation engineering not only provides physical infrastructure, but through systemic planning and spatial integration, it acts as an agent of economic transformation that creates "agricultural economic corridors"—strategic growth zones that efficiently connect production centers, processing centers, and consumer markets. In the context of the development of agrarian regions such as Kalimantan, the national road network is not just a connecting route between villages or cities, but a vital foundation that supports the entire architecture of the agricultural business system, encouraging the transformation from fragile subsistence agriculture to modern, integrated, and highly competitive agribusiness. This is in line with the experience of various countries in Africa and Asia, where development corridors such as SAGCOT (Southern Agricultural Growth Corridor of Tanzania), LAPSSET (Lamu Port-South Sudan-Ethiopia Transport), and Beira Corridor in East Africa have been shown to drive the commercialization of agriculture through the development of planned transportation infrastructure, create a vibrant local economic network and attract agribusiness investment ([83]. These corridors not only shorten physical distances, but also shorten the economic distance between farmers and markets, opening up space for economies of scale, logistics efficiency, and vertical integration in the value chain.

This kind of agribusiness transformation is only possible if technological modernization goes hand in hand with visionary transportation planning. [84] emphasized that the agro-food sector development strategy in rural areas must involve both elements to encourage innovation and attract investment. In the context of Kalimantan, this means that the construction of national roads must be designed not only to connect the two points, but to integrate the production area with processing centers and export ports, thus allowing the emergence of downstream industries such as palm oil mills, rubber processing, or horticultural product packaging units. [85] asserts that the transformation of rural areas depends on holistic regional planning, reliable infrastructure, and integrated connectivity to drive the productivity of the agro-industrial sector. An integrated agribusiness model, as proposed [86], suggests that by connecting production, processing, and markets through efficient logistics networks, structural economic transformations can occur that drive poverty reduction and increased local added value. However, the development of agricultural economic corridors also carries risks, especially related to land conversion and overexploitation of natural resources. Studies of the Laos corridor show that although transportation infrastructure succeeds in sparking market integration and economic growth, without rigorous spatial planning, development can lead to mass deforestation and loss of local people's access to land [20]. Therefore, transportation techniques must be applied within an inclusive and sustainable framework of regional planning, not only for economic efficiency, but also for social justice and ecosystem protection.

In Nigeria, [87] found that rural transport infrastructure is a key lever for agribusiness transformation, enabling farmers to increase productivity and access to markets. Similar findings emerged from Nepal, where the transition from subsistence agriculture to commercial agribusiness relies heavily on infrastructure development and market access [88]. [89] emphasized that agricultural transformation acceleration policies in Africa explicitly include the construction of agro-corridors and agricultural industrial zones to create economies of scale and attract private investment. In Rwanda, [90] showed that strengthening agribusiness supply chains in rural areas requires not only a good transportation system, but also financial and institutional planning that supports local economic integration. Meanwhile, [91] highlight that agribusiness transformation in South Asia cannot occur without a combination of infrastructure access and institutional reforms that drive modernization of the agricultural sector. Thus, the national road network in Kalimantan should be seen not only as a physical project, but as a strategic tool for rural economic development. Through transportation engineering planning that is integrated with agrarian policies, spatial planning, and industrial development, roads can be a catalyst for agribusiness corridors that encourage the emergence of production clusters, attract investment in the processing sector, and strengthen regional food security. In this scenario, transportation techniques transform from a technical discipline to an architect of economic space, which reshapes the structure of Kalimantan's agriculture from a fragmented and vulnerable system to a productive, inclusive, and sustainable agribusiness ecosystem. Considering all the multidimensional analyses that have been described—ranging from technical, economic, social, ecological, to policy governance aspects—it can be concluded that the construction of the National Road Network in Kalimantan is not just a physical infrastructure project, but an instrument of strategic transformation that determines the future direction of national development in eastern Indonesia. Roads built amid extreme geographic challenges, unstable peatlands, and vulnerable tropical rainforests must be designed not only to connect places, but to connect opportunities, maintain ecosystem balance, and strengthen spatial justice. The success of this infrastructure depends on the holistic integration of engineering innovation, participatory public policy, respect for the rights of indigenous peoples, and a commitment to the principles of sustainable development. Without a comprehensive and sustainable approach, accelerating road construction risks widening gaps, damaging the environment, and creating long-term social conflicts

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CHAPTER 3

INDUSTRIAL MANAGEMENT IN INFRASTRUCTURE DEVELOPMENT

Novandi Arisoni | Suharsono

3.1. The Role of Industrial Management in Infrastructure Projects

Industrial management plays a crucial role in the success of infrastructure projects, especially the construction of the national road network in Kalimantan which has high geographical and environmental complexity. In this context, industrial management does not simply regulate the implementation of projects, but acts as a strategic system that efficiently brings together project planning, procurement, execution, and control. Like a production manager in a large factory, road project management is in charge of optimizing the entire "production line" in the field: from heavy equipment, materials such as aggregates and asphalt, to labor. Approaches such as the Critical Path Method (CPM) and Program Evaluation and Review Technique (PERT) are used to construct realistic and adaptive schedules, especially due to the challenges of Borneo's topography and climate. Meanwhile, the principles of lean construction and the application of technology such as Building Information Modeling (BIM) have also begun to be used to minimize waste of time and costs and improve the accuracy of decision-making in the field. The use of BIM has been shown to significantly improve efficiency in planning and scheduling construction projects. A study [1] identifies five key areas of BIM application in scheduling, including data integration and supply chain management, that support more accurate and coordinated decision-making. Furthermore, [2] show that BIM 4D can reduce errors in resource allocation as well as improve coordination between stakeholders, especially in infrastructure projects such as roads. Meanwhile, [3] emphasized the importance of technical readiness and human resource training in comparing manual and automated approaches in 4D BIM based scheduling, suggesting that technology alone is not enough without adequate organizational capacity support. On the other hand, the integration of BIM with Lean construction principles offers a holistic approach to overcoming project delays. [4] found that the combination of these two methods is effective in reducing the factors that cause delays, especially in residential building projects, although their relevance also applies to infrastructure projects. A similar approach is supported [5], who highlight the role of technological innovation and the Industrial Revolution 4.0 in transforming construction project management as a whole. In the context of scheduling methodology, [6] conducted a systematic study of 332 articles and recommended the integration of conventional methods such as PERT and CPM with the latest digital technologies to close research gaps and strengthen scheduling practices. Finally, on projects that implement modular construction and prefabrication—which is increasingly relevant for remote areas—human-based risk management and supply chain integration are crucial. Research [7] and [8] emphasizes the importance of a systemic approach to managing risk and increasing productivity in this context, which can also be applied to road projects with complex logistical challenges. Overall, the findings of these various study groups demonstrate the need for an integrated approach that combines digital technologies, lean management, and risk management strategies to improve efficiency, timeliness, and sustainability in construction projects.

Recent studies have shown significant developments in the application and development of the CPM method in various project contexts. [9] proposes a new approach called Critical Path Segments (CPS) as an improvement of the classic CPM. CPS is designed to overcome limitations in relationships between activities as well as increase managerial flexibility in project scheduling. Meanwhile, [10] applied CPM in manufacturing production scheduling and successfully demonstrated that critical line identification can accelerate project completion by up to 96 days, confirming the effectiveness of CPM in an industrial context. In the face of project uncertainty, [11] evaluated managerial flexibility in CPM schedules through a Monte Carlo-based risk simulation approach. The results show that CPM can be extended in usefulness by taking into account the uncertainty and variability of the project. Furthermore, [12] compared the effectiveness of CPM and Linear Scheduling Method (NGO) in water canal construction projects. The study concluded that NGOs are superior in time and cost efficiency, yet CPM remains relevant in the context of projects with a certain complexity. These studies show that CPM continues to evolve and remains adaptive to the diverse challenges and needs of modern projects.

Table 3.1. Stages of CPM

Code	Activities	Duration (days)	Predecessor
A	Study topography	3	-
B	Land reclamation	4	A
C	Road base pavement (subgrade)	5	B
D	Drainage installation	3	B
E	Foundation pavement (base course)	4	C
F	Paving (surface course)	2	E
G	Final testing and handover	1	D, F

Source: Author analysis, 2025

The CPM is a project scheduling technique used to identify the sequence of activities that determine the shortest project completion time. In the CPM model for the construction of access roads to the construction area, the process begins with an initial activity in the form of a topographic study (A) which takes 3 days (Table 3.1.). After the study is completed, it is followed by land reclamation (B) for 4 days, which is a prerequisite for the next two lines of work: road base pavement or subgrade (C) and drainage installation (D). Activity C takes 5 days and continues to the foundation pavement or base course (E) for 4 days, then continues with paving or surface course (F) for 2 days. Meanwhile, activity D is 3 days long and is directly connected to the final activity, i.e. final testing and project handover (G), which is also dependent on the completion of F and is 1 day long.

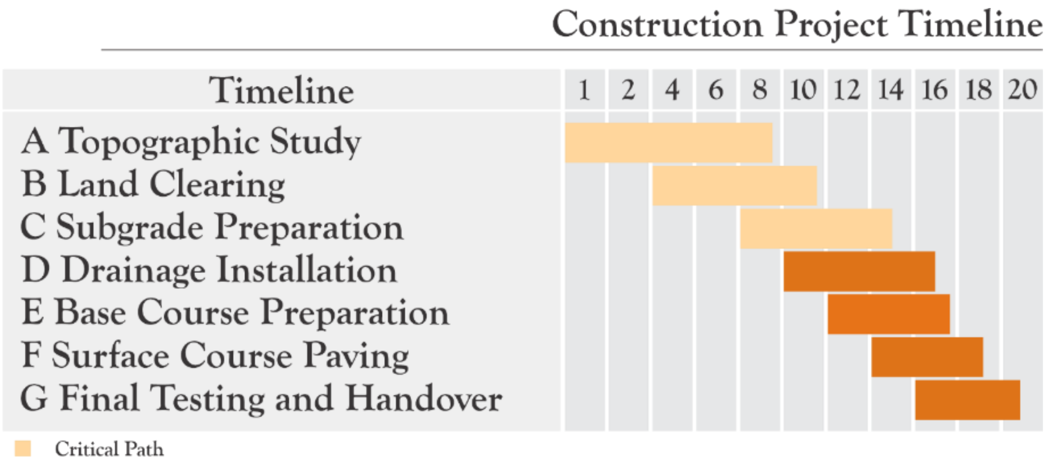

Figure 3.1. Construction Project Timeline

Source: Author analysis, 2025

Through CPM analysis (Figure 3.1.), the critical path of the project consists of a series of activities A , → B , → C , → E , → F → G with a total duration of 19 days. This line is the longest duration and does not have a time allowance (float), so delays in one of the activities on this line will have a direct impact on the delay of the entire project. Activity D, while important, is off the critical path because it has flexibility in scheduling. This CPM model provides clear guidance for project managers in allocating resources efficiently, prioritizing oversight of critical activities, and minimizing the risk of project delays. The development of the PERT continues to evolve to improve the accuracy of schedule predictions under complex and uncertain project conditions (Figure 3.2.). [13] developed a project delay prediction algorithm by utilizing PERT in modeling the uncertainty of activity time in dynamic construction environments. In the context of improving the accuracy of time estimation, [14] proposes an extended PERT approach using Beta and Log-Normal distributions combined with Bayesian updates. This approach has been proven to improve precision in scheduling high-rise building projects. Meanwhile, [15] combined the PERT method with ISSCD to handle construction projects in developing countries that experience funding uncertainty. This method results in a more flexible schedule and is adaptive to changes in financial conditions. The overall study reflects that PERT continues to undergo methodological diversification to address challenges in increasingly complex and uncertain project prediction and planning.

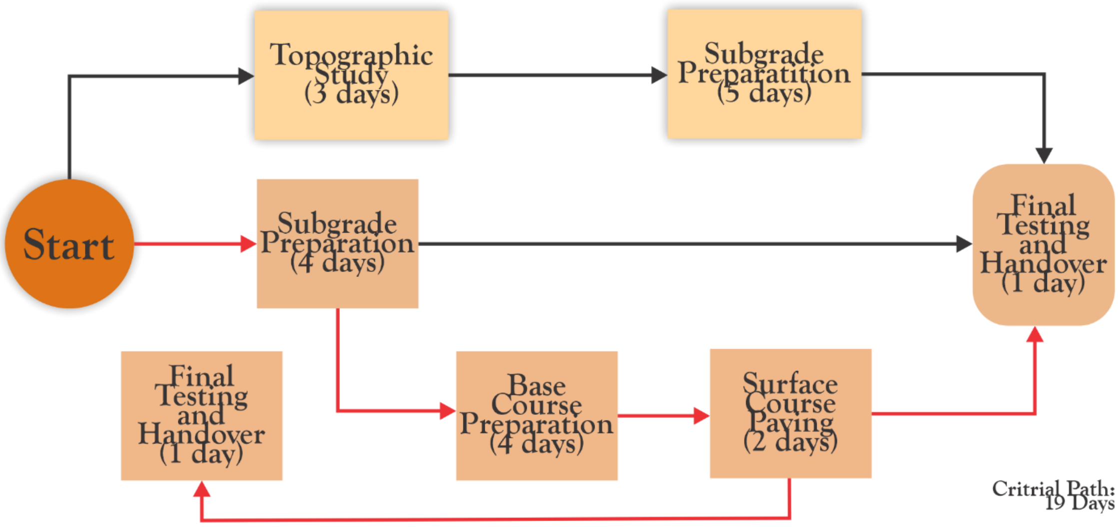

Figure 3.2. Network Diagram Critical Path

Source: Author analysis, 2025

BIM has become an important instrument in the digital transformation of the construction industry, particularly in improving efficiency, collaboration, and project control. [16] through a case study showed that the use of BIM in project planning and execution can improve team time and communication efficiency through 3D modeling and cross-software data integration. [17] also emphasized that BIM significantly strengthens project efficiency, coordination between stakeholders, and risk management in construction projects. In a more comprehensive approach, [18] demonstrated the application of BIM for various functions, including design, clash detection, cost estimation, and facility management, with a real impact on improving collaboration and reducing design errors. The study [19] evaluated the implementation of BIM on the Central Bank of Iraq project, and emphasized the importance of guiding the implementation as well as the adoption of BIM AEC (UK) protocols to encourage more effective collaboration. Meanwhile, [20] through quantitative analysis proves that BIM significantly contributes to time and cost efficiency, quality improvement, and sustainability in multi-storey housing projects in Saudi Arabia. These findings consistently show that BIM is not only a visualization tool, but also a strategic platform for integrating the entire construction project lifecycle.

3.2. Cost and Time Analysis in National Road Projects

Cost and time analysis are two fundamental pillars in the management of national road infrastructure projects. The cost component includes all expenses from the planning stage, material procurement, labor wages, heavy equipment rental, to maintenance costs. Meanwhile, the time component includes scheduling each phase of construction, from land maturation to final finishing. These two components are closely intertwined—time delays will have an impact on cost overruns, both in operational and opportunity costs. Project feasibility is assessed from the ability to achieve targets with a set budget, while sustainability refers to the ability of the infrastructure to provide long-term benefits that are proportional to the investment incurred. Without a comprehensive analysis of these two aspects, projects risk cost overruns or delays that could disrupt regional economic connectivity.

The study of [21] revealed that the average cost overrun in road projects in Ethiopia reaches 18%, and can even jump to 61% due to weak risk management and unrealistic scheduling, while [22] add that administrative obstacles such as delays in land acquisition also extend the duration of projects and increase the cost burden. To prevent budget deviations, [23] emphasize the need for accurate cost estimates from the early stages, including road lifecycle cost calculations, to support more reliable long-term planning. In the context of innovation, [24] prove that the application of machine learning to predict toll road construction costs can improve the accuracy of estimates through historical data-based modeling. In addition, project characteristics such as contract methods, facility types, and infrastructure capacity also affect cost performance, as shown [25] in an analysis of 170 road projects. In Norway, [26] found that the implementation of a quality-gated framework was successful in suppressing cost deviations, although external factors such as extreme weather and geographical conditions remained a challenge that remained difficult to control. Financial risks are also of particular concern, especially on expressway projects with complex topography that rely on external funding. [24] highlights the importance of risk management against interest rate fluctuations and dependence on external sources of funds. Furthermore, the socioeconomic impact of delays and high costs should not be ignored. Thus, the synergy between accurate cost estimation, realistic scheduling, comprehensive risk management, and socio-economic considerations is key in realizing efficient, timely, and sustainable national road projects (Table 3.2.).

The following is the preparation of a simulation of the national road project cost and time analysis method in the form of a table. This simulation is based on the Monte Carlo approach, PERT/CPM, and integration with BIM that is widely used in large-scale construction project management practices. This model is designed to map the stages and techniques used in predicting the feasibility of a project in cost and time, taking into account the uncertainties and risks that come with it. Simulation method in Table 3.2. reflects a multidisciplinary approach used internationally in predicting and managing the cost and timing of road projects. The use of historical data [21] is the foundation for compiling basic assumptions. Furthermore, the daily duration and cost variables were analyzed through the Monte Carlo method and machine learning to obtain a probabilistic distribution of project results [24].

Table 3.2. Simulation of Cost and Time Analysis Methods in National Road Projects

Simulation Stage	Methods/Approaches	Purpose and references
1. Historical Data Collection	Similar project data and case studies	Compile a baseline of project duration and cost based on real experience [21]
2. Schedule Simulation (Duration)	PERT/CPM, Monte Carlo Simulation	Modeling project duration variability and delay risk [26]
3. Project Cost Estimate	Statistics Descriptive, Machine Learning (ANN)	Estimate the total cost of a project based on a random input of costs per day [24]
4. Cost-Time integration	Time-Cost Trade-Off Analysis	Analyze the effect of acceleration or delay on the total cost of the project [25]
5. Project Risk Simulation	Sensitivity Analysis, Scenario Schema	Testing the impact of uncertainty (weather, materials, etc.) on schedules and costs [27]
6. Model Visualization and Validation	4D BIM	Visually present schedules and costs and identify field conflicts [2]
7. Evaluation & Decision Making	Output Statistics, Feasibility Probability	Generate outputs such as cost probabilities ≤ budgets in random scenarios [23]

Source: Author analysis, 2025

Risk simulations are added to accommodate external factors such as weather and socio-economic disturbances [27]. The visualization stage using 4D BIM [2] allows for real-time spatial and temporal validation of the project. As such, these simulations can help project decision-makers more accurately anticipate cost overruns and delays, and provide a solid foundation for data-driven mitigation strategies. This simulation uses a Monte Carlo approach to address uncertainty in two main parameters, namely project duration and daily operational costs. In this scenario, the project duration is assumed to be in the range of

150 to 210 days, with an average value of 180 days. Meanwhile, operational costs per day are estimated to be between 20 million to 35 million rupiah, with an average of 25 million rupiah. Both variables were randomly modeled using normal distributions and simulated 10,000 times to produce a probabilistic distribution of the total project cost. The final result of the simulation is in the form of estimated values of the total cost that reflect real possibilities based on the fluctuations of the two parameters. When formulated with Collabs as shown in Figure 3.3.

```
import numpy as np
import matplotlib.pyplot as plt
# Number of simulations
n_simulations = 10000
# Project duration distribution parameters (in days)
mean_duration = 180
std_duration = 15
project_duration = np.random.normal(mean_duration, std_duration, n_simulations)
# Daily cost distribution parameters (in million IDR)
mean_daily_cost = 25
std_daily_cost = 4
daily_cost = np.random.normal(mean_daily_cost, std_daily_cost, n_simulations)
# Total project cost (in million IDR)
total_project_cost = project_duration * daily_cost
# Plot simulation results
plt.figure(figsize=(10, 6))
plt.hist(total_project_cost, bins=50, edgecolor='black')
plt.title("Distribution of Total National Road Project Cost\n(Monte Carlo Simulation)")
plt.xlabel("Total Project Cost (million IDR)")
plt.ylabel("Frequency")
plt.grid(True)
plt.show()
# Basic statistics
print(f"Mean total project cost: {np.mean(total_project_cost):,.2f} million IDR")
print(f"Maximum total project cost: {np.max(total_project_cost):,.2f} million IDR")
print(f"Minimum total project cost: {np.min(total_project_cost):,.2f} million IDR")
print(
f"95% probability that the project cost will not exceed: "
f"{np.percentile(total_project_cost, 95):,.2f} million IDR"
)
```

Figure 3.3. Monte Carlo Simulation Code

Source: Author analysis, 2025

Figure 3.3. presents the results of Monte Carlo simulations conducted to predict the total cost of national road projects by taking into account uncertainties on implementation duration and daily operational costs. This simulation generates a probabilistic distribution of the project's final cost estimate, which can be used to evaluate budget feasibility and establish a more rational cost buffer.

From the results of the simulation conducted (figure 3.4.), it was obtained that the average total project cost was around 4,500 million rupiah. In addition, there is a 95% probability that the project will be completed at a cost of less than 5,100 million rupiah.

These findings suggest that the project is within the limits of cost-eligibility with a controllable level of risk. This information is very useful for project managers in drafting financial plans and establishing adequate budget buffers. By considering the distribution of these results, decision-makers can be better prepared for potential cost overruns, as well as design mitigation strategies to avoid financial failures during project implementation. Road construction in Kalimantan faces a number of unique challenges that are significantly different compared to other regions of Indonesia, mainly due to extreme geographical and ecological conditions. One of the main challenges is the highly unstable peatlands and swamplands, which require special methods of soil stabilization and adaptive construction techniques. In other tropical regions such as the Republic of the Congo and the Democratic Republic of the Congo, infrastructure projects around rainforests are also faced with similar problems, especially in land management and the environmental impacts of clearing forests for road construction [28].

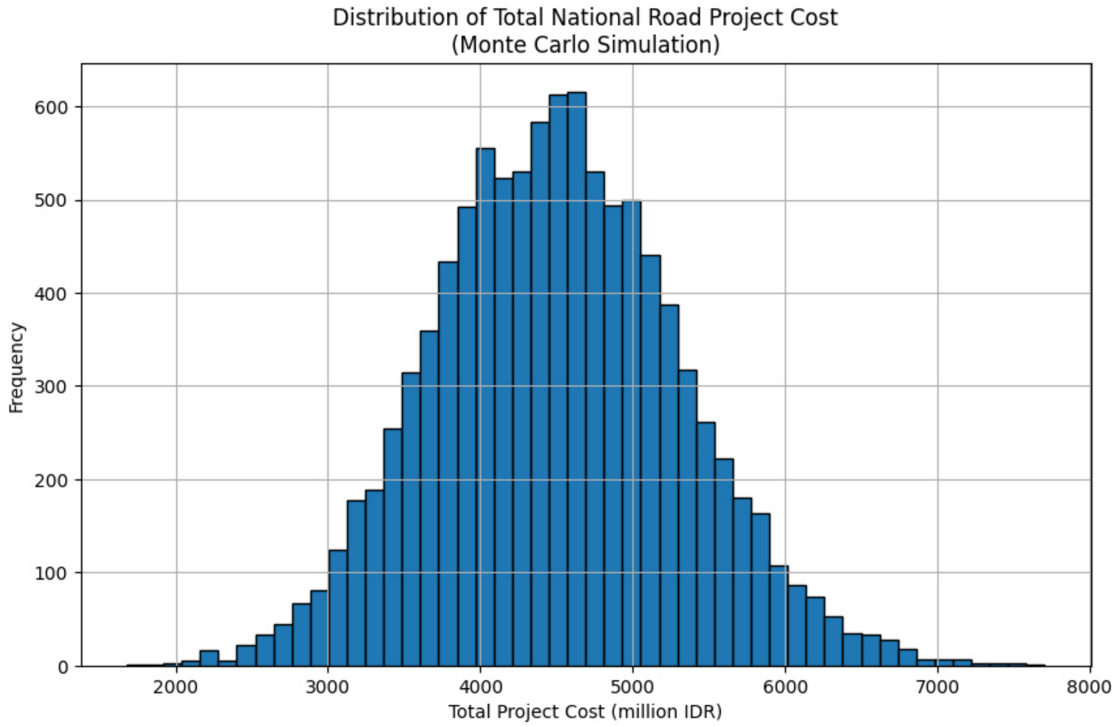

Figure 3.4. Distribution of Total Costs of National Road Projects (Monte Carlo Simulation)

Source: Author analysis, 2025

In addition, the density of forests and hilly terrain requires a massive *cut and fill* process , which significantly increases the cost and time of labor. A study by [28] shows that road construction in hilly areas is prone to soil erosion and biodiversity degradation, so a route design approach that takes into account ecological damage with cost optimization through genetic algorithms is needed. This is particularly relevant in Kalimantan, where the clearing of roads across primary tropical forest areas must take into account environmental conservation. The next challenge is the very high logistics costs. Due to limited access and a lack of available road networks, materials such as asphalt, cement, and iron must be transported by sea from Java or Sulawesi, then distributed by river or limited land routes. Studies in Laos' economic corridors show that land-use changes due to infrastructure development can lead to space-use conflicts and spikes in distribution costs, especially in hard-to-access inland areas [29]. Overall, the cost of road construction in Kalimantan, which can reach 2-3 times that of Java, is very understandable in the context of complex technical, ecological, logistical, and climatic challenges. A multidisciplinary approach that integrates civil engineering, ecology, as well as geographic information systems is needed to design infrastructure solutions that are not only technically and financially feasible, but also environmentally sustainable.

3.3. Implementation of Cost Breakdown Structure (CBS)

CBS is a systematic method to break down the total cost of a project into more detailed and measurable components. In the context of a national road project, CBS starts from the highest level, namely the total project cost, then breaks down into direct cost and indirect cost. Direct costs include materials (aggregate, asphalt, cement), workers' wages, heavy equipment rentals, and subcontractors. Indirect costs include office overhead, insurance, licensing, and contingencies. Each category is then further detailed—for example, the cost of materials is broken down by material type with estimated volume and unit price. CBS allows project managers to identify the most significant cost components, exercise tighter budget controls, and anticipate potential cost overruns. This structure also facilitates a more transparent and accountable tender process. [30] emphasizes the importance of CBS in the management of projects based on the SAP S/4HANA system that allows for the systematic integration of costs from all components of the EPC project. Effective implementation of CBS helps identify dominant cost posts and supports a more transparent tender process. The method of implementing CBS in the National Road Project, begins with Project Total Cost Identification, the initial stage is to determine the estimated total project budget based on planning documents, historical data of similar projects, and project geographical conditions. This initial estimate is the starting point for the CBS. Second, the Top-Level Cost Categorization, which is indicated by the total cost of the project, is classified into two broad categories, namely direct cost: including materials, labor, equipment, and subcontractors. Indirect Cost: includes general project office costs (overhead), insurance, project permits, taxes, and contingency reserves. Third, Cost Element Decomposition, each cost category is broken down into more detailed elements. Example: Material: Aggregate, asphalt, cement, geotextile. Equipment: Heavy equipment rental (excavator, grader, compactor). Labor: Salaries of field workers, technicians, foremen, and supervisors. Overhead: Office logistics, communications, security, and utilities costs. Fourth, the Unit Cost & Quantity Definition, for each cost element, is defined as the unit of measure (e.g., m^3, ton, working day) and volume vital based on the technical drawings and project specifications. Fifth, Unit Price Estimation, the unit price is determined from the latest market data, the unit price catalog (HSPK), or the results of supplier negotiations. This is multiplied by the volume at the previous stage to get the subtotals of each element. Sixth, CBS Hierarchical Structure Development, all cost data is compiled in the form of a CBS hierarchy (usually 3–5 levels) starting from total costs to granular elements. The format of the CBS table or tree structure is often used for visual representation. Seventh, Budgeting & Procurement integration, CBS is used as the basis for the preparation of Bill of Quantity (BoQ), Definitive Cost Estimate), as well as tender documents for the procurement of goods and services. Eighth, Cost Control & Tracking, CBS is the main reference in actual cost vs. budget reporting (variance). Tracking systems such as Earned Value Management (EVM) or ERP software are used to monitor the cost performance of each element of CBS. Finally, the CBS should be revised as per design changes, market price changes, or unforeseen risks (*e.g.,* extreme weather, logistical disruptions), to maintain the validity and accuracy of the data. This method makes CBS not only a cost estimation tool, but also a dynamic cost control system that is fully integrated in the life cycle of a road infrastructure project, from the planning stage to operation.

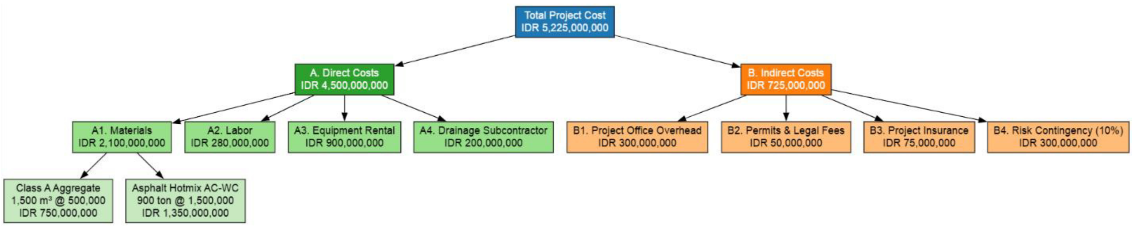

Figure 3.5. CBS Estimate of 1 Km National Road Project in Kalimantan.

Source: Author analysis, 2025

The following is a simulation of the implementation of the CBS in national road projects. This simulation aims to provide a practical overview of how CBS is used to break down total project costs into cost components that can be further controlled, monitored, and analyzed. Figure 3.5. is a CBS diagram for a 1 km national road construction project in Kalimantan. The diagram shows a hierarchy of the project's cost structure, from the total cost of the project to the breakdown of the direct and indirect cost components. This CBS simulation shows a total estimated cost of IDR 5,225,000,000, where direct costs dominate with a portion of around 86% (IDR 4,500,000,000), while indirect costs reach 14% (IDR 725,000,000). In the diagram, the green section depicts direct cost components such as materials, labor, heavy equipment rentals, and drainage subcontractors, with materials being the largest contributor of IDR 2,100,000,000 (consisting of class A aggregate and AC-WC hotmix asphalt). Meanwhile, the orange section shows indirect costs, including project office overhead, licensing and legality, project insurance, and risk contingencies of 10%. The dominance of material and heavy equipment costs, as depicted in this CBS structure, reflects the high logistical burden in the Kalimantan region which has limited access and requires the mobilization of resources across islands, thus affecting the total project cost.

3.4. Implementation EVM

EVM is a project management technique that integrates the scope of work, schedule, and costs to objectively measure project performance. EVM uses three main parameters: Planned Value (PV), Actual Cost (AC) or actual costs incurred, and Earned Value (EV) or the value of work that has been completed. From these three parameters, performance indicators such as the Cost Performance Index (CPI) and Schedule Performance Index (SPI) can be calculated. In road projects in Kalimantan, EVMs allow early detection if the project experiences delays or cost overruns. For example, if in the 6th month the project should have reached 50% progress at a cost of IDR 50 billion, but in fact it is only 40% at a cost of IDR 55 billion, then CPI and SPI will show performance below the target. This information allows for quick and precise corrective decision-making. [31] found that a mature Earned Value Management System (EVMS) system can bridge the gap between project planning and realization, while improving project performance predictability. [32] also proves that periodic CPI and SPI calculations are effective in detecting project deviations before they become major failures. Even new approaches using machine learning have been developed to improve the accuracy of EV predictions through automated pipelines [33].

Figure 3.6. systematically describe the stages of implementing EVM in infrastructure projects, especially in national road construction projects. This diagram consists of seven main steps arranged in a hierarchical manner to integrate the overall aspects of cost, time, and project performance. The first step is the determination of the project scope and the Work Breakdown Structure (WBS), where all project activities are outlined into measurable work packages such as earthworks, paving, drainage, and road markings. This stage is

important so that each element of the project has a clear output and can evaluate its progress.

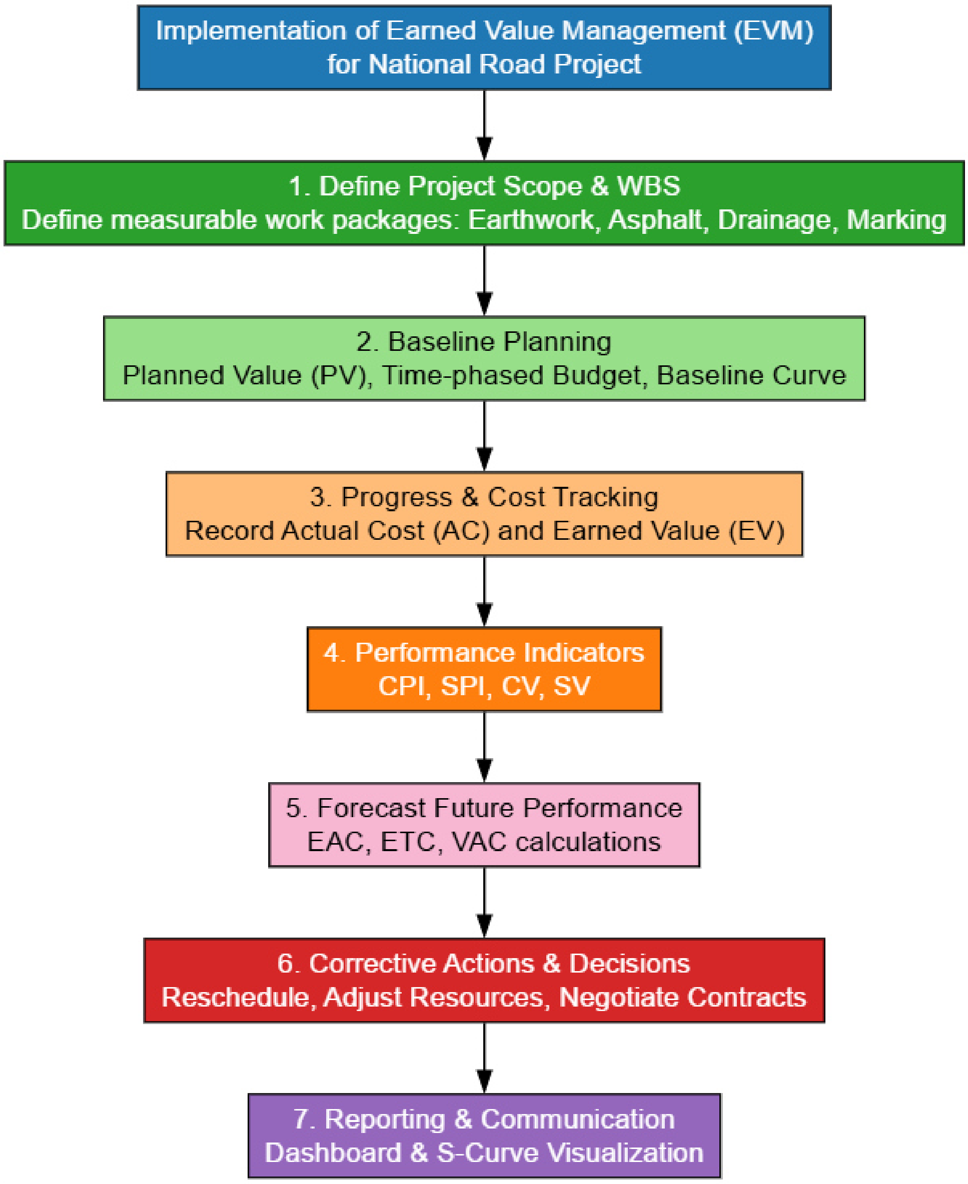

Figure 3.6. Implementation of EVM for National Road Projects

Source: Author analysis, 2025

Furthermore, the second stage is baseline planning, which includes the preparation of PV, the determination of a time-phased budget, and the formation of a baseline curve as a reference for comparison between plans and realizations during the implementation period. The third stage is tracking physical progress and actual costs, which is done by recording the AC, which is the real cost that has been incurred, and the EV, which is the value of the work that has actually been completed. This data is the basis for calculating project performance indicators in the fourth stage, namely performance indicators. Four main indicators are used, namely the CPI and SPI to measure cost and time efficiency, and Cost Variance (CV) and Schedule Variance (SV) to show the difference between the value of the plan and the realization. The fifth stage is forecast future performance, where the project manager calculates Estimate at Completion (EAC) to estimate the total final cost of the project, Estimate to Complete (ETC) to determine the costs still needed, and Variance at Completion (VAC) to find out the difference between the initial budget and the final projection. The results of these calculations are used in the sixth stage, which is corrective actions and decision-making, such as adjusting schedules, redistributing labor and equipment, renegotiating with subcontractors, or even submitting more funds if needed. The final stage, which is the reporting and communication of project progress, is presented through periodic dashboards (weekly or monthly) that visually display project performance, including S-curve graphs to illustrate the relationship between plans, realizations, and deviations that occur during the project. Figure 3.6. emphasized that the implementation of EVM is not only a reporting tool, but a proactive project management control system. Through this approach, deviations from the plan can be detected early, allowing for quick and informed decision-making to keep projects on budget and schedule. In the context of national road projects in Indonesia, especially in geographically challenged areas such as Kalimantan, the application of the EVM method is very relevant to improve transparency, resource efficiency, and accountability in the use of public funds.

3.5. Time and Cost Trade-offs in Project Acceleration

The concept of trade-off between time and cost is a classic dilemma in construction project management. Accelerating project completion by adding work shifts from one shift (8 hours) to two or three shifts (16-24 hours) can cut project duration by 40-50%. However, this strategy carries the consequence of a substantial increase in costs. Overtime costs for workers can reach 150-200% of normal wages, night shift productivity tends to decrease by 20-30%, the need for more lighting, increased risk of work accidents, and faster heavy equipment wear. In addition, the quality of work on the night shift has the potential to decline due to worker fatigue and limited visibility. The trade-off analysis must consider not only the financial aspects but also the impact on the quality, work safety, and operational sustainability of the contractor. [34] in the context of construction 4.0 show that the acceleration of time must be compensated by increased accuracy in life cycle cost and environmental cost, especially in bridge and public infrastructure projects. While [35] used the entropy approach in construction projects to evaluate the dynamic conditions of projects that are accelerating, and showed that acceleration often increases the complexity and uncertainty of projects.

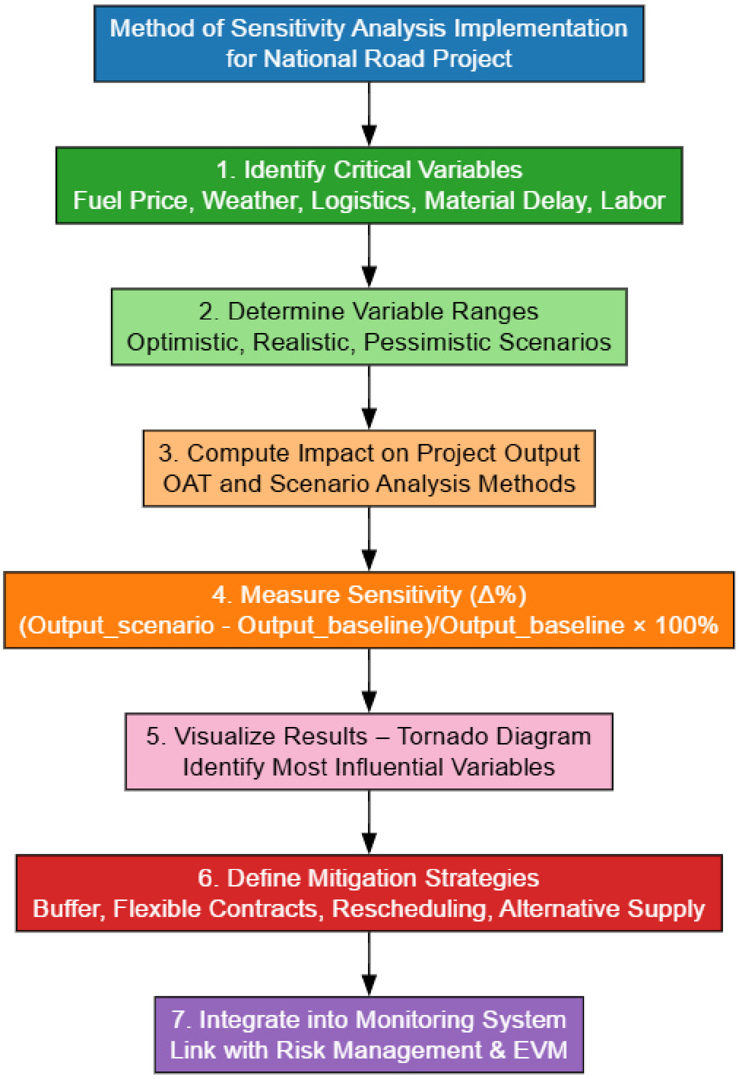

Figure 3.7. Methods of Applying Sensitivity Analysis in National Road Projects

Source: Author analysis, 2025

Figure 3.7. displays systematic steps in the application of Sensitivity Analysis to infrastructure projects, especially national road construction projects in geographically challenging areas such as Kalimantan. This diagram serves to explain how project managers can identify, analyze, and manage the critical variables that have the most impact on project costs and execution time. This process is important in risk management because it helps understand how much changes in a given factor—such as fuel prices, weather conditions,

material delays, logistics costs, or labor productivity—can affect the total cost and duration of the project. The first step in the diagram is the identification of the project's critical variables, i.e. recognizing the key factors that have the potential to cause deviations in project performance. After the variables are determined, the second stage, namely the determination of the range of variable values, is carried out by compiling three main scenarios: optimistic, realistic, and pessimistic. This approach provides an overview of how best, normal, and worst conditions can affect the project, for example the change in fuel prices from Rp13,000 to Rp17,000 per liter. The third stage is the calculation of the impact on project output, which is carried out using the One-at-a-Time (OAT) method or scenario analysis, where one or more variables are changed to see their impact on project results such as total cost or completion time. The next stage is sensitivity measurement (Δ%), where each change in output is compared to the baseline (initial reference value). The results show how sensitive the project is to changes in each variable. The higher the sensitivity value, the greater the potential risk to be anticipated. The fifth step is the visualization of results through the Tornado Diagram, which is used to visually display the variables with the greatest influence on the project's performance.

The variable with the highest impact is placed at the top of the diagram, resembling the shape of a tornado, making it easier for project managers to identify dominant risk factors. After knowing the most influential variables, the sixth stage is the establishment of mitigation strategies, such as setting up cost and time buffers, implementing flexible contracts that accommodate fuel price escalations, rescheduling weather-sensitive work, and providing alternative material supply chains. The final step is the integration of the analysis results into the project monitoring system, which is linked to the EVM framework for integrated cost and time control. Figure 3.7. shows that Sensitivity Analysis is an important tool in strategic decision-making on national road projects. By implementing this method, project managers can be better prepared to deal with external uncertainties, reduce the risk of delays and cost overruns, and improve the effectiveness of project controls. This approach also strengthens transparency and accountability in the management of public funds, making it an important practice in the management of national-scale infrastructure projects in Indonesia.

3.6. Application of Sensitivity Analysis

Sensitivity analysis in the context of road projects in Kalimantan identifies critical variables that can affect the success of the project. Fluctuations in the price of diesel fuel used for heavy equipment and material transportation can change the cost structure by up to 15-20%. The increase in fuel prices of Rp 1,000 per liter can increase daily operational costs by millions of rupiah. Extreme rainfall that exceeds predictions can halt earthworks and paving, causing adverse idle time. Every rainy day can delay progress by 2-3 days due to soil conditions that must be drained. Constraints on access to raw materials, such as scarcity of quality aggregates or delays in asphalt delivery, can stop the entire production chain. Sensitivity analysis uses optimistic, realistic, and pessimistic scenarios for each variable, then calculates their impact on the total cost and project completion schedule. [36] applies an ITTO-based approach to risk management of EPC projects that shows that the use of Monte Carlo simulations can anticipate delays due to external risks such as logistics and cross-border regulation. Meanwhile, [37] in their review of cash flow modeling stated that uncertainty in the price of building materials and payment schedules greatly affects the continuity of cash flow of construction projects (Figure 3.8.).

A systematic process flow used to analyze risks, evaluate their impacts, and formulate mitigation strategies in the context of project management, especially those of a complex nature such as infrastructure development. This process consists of four main stages that are interrelated. The first stage, Identification of Critical Variables, involves determining key factors that have the potential to affect the smooth running of the project. In this example, those variables include labor productivity, logistics costs, material delays, extreme weather, and fuel prices—all elements that are highly relevant in a road or building construction project.

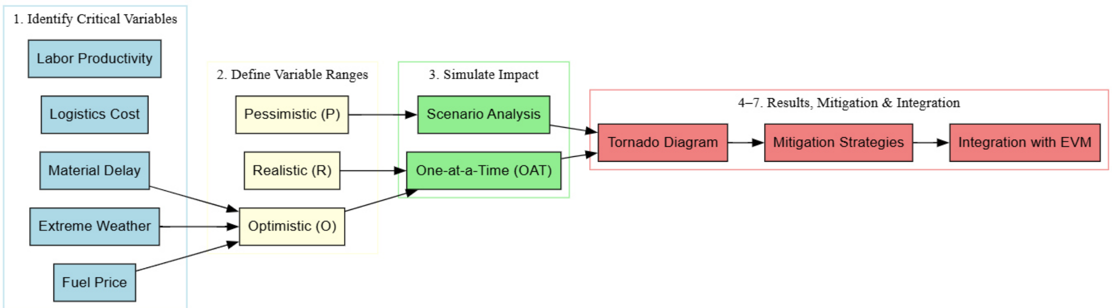

Figure 3.8. Risk Analysis and Mitigation Process Flow in Infrastructure Project Management

Source: Author analysis, 2025

The second stage, Defining Variable Ranges, establishes three possible scenarios for each variable: optimistic (O), realistic (R), and pessimistic (P). This allows for a more comprehensive analysis of a wide range of possible conditions, rather than just one single assumption. The third stage, Impact Simulation, uses two methods: Scenario Analysis and OAT. This method simulates how changes to one or more variables at the same time will affect the outcome of the project. The simulation results are then processed into visualizations in the form of a Tornado Diagram in the fourth stage. The fourth stage, Outcomes, Mitigation Strategies, and integration, is at the core of the decision-making process. Tornado diagrams help identify which variables have the most impact on project outcomes (usually shown as horizontal bars with length proportional to their impact). Based on this identification, the project team can formulate the right Mitigation Strategy to mitigate the greatest risks. The last step is integration with EVM, which is aligning findings and mitigation plans with the project's value-added management system, so that cost, time, and performance control can be carried out in an integrated and data-driven manner.

3.7. A Holistic Approach to Infrastructure Project Evaluation

The paradigm of national road project evaluation has shifted from simply measuring physical output (road length, width, thickness) to a more comprehensive assessment. Systemic efficiencies include how projects are integrated with existing transport networks, their contribution to reduced travel time and regional logistics costs, and their impact on local economic development. Long-term reliability is assessed from the durability of the construction against predicted traffic loads, resistance to extreme weather conditions, and the need for routine maintenance. The evaluation also considers social aspects such as increased community accessibility to public services, the environmental impact of land clearing, and financial sustainability for maintenance. This holistic approach ensures that infrastructure investments not only generate physical assets, but also create sustainable economic and social added value for the people of Kalimantan. [34] emphasize the importance of integrating Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) to evaluate the long-term performance of road and bridge infrastructure in the context of construction 4.0. Project evaluations based on digital systems such as BIM and Bridge Information Modeling (BrIM) not only increase decision-making transparency, but also ensure that projects contribute to regional connectivity and local economic development.

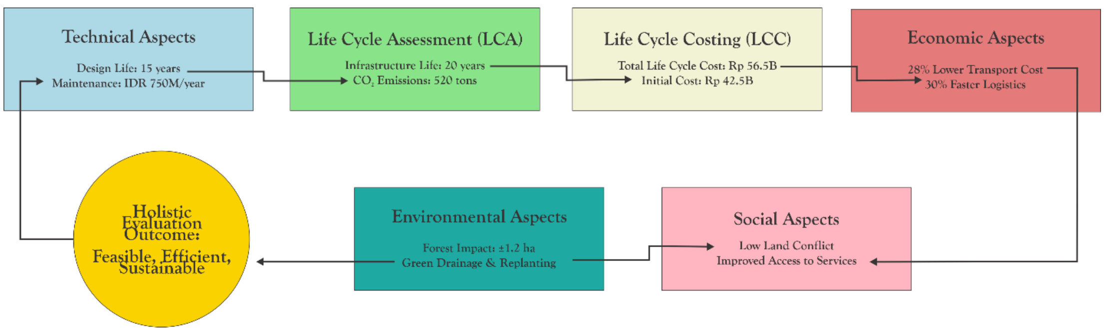

Figure 3.9. Holistic Evaluation of the Feasibility of Infrastructure Projects Based on Technical, Economic, Environmental, and Social Aspects.

Source: Author analysis, 2025

This method ensures that the evaluation of road infrastructure projects is no longer limited to the length or width of the road, but includes real and sustainable impacts on the transportation system, society, and the environment. The application of LCA, LCC, and digital modeling strengthens transparent and data-driven decision-making. A holistic evaluation framework that brings together four key dimensions—technical, economic, environmental, and social—to assess the feasibility and sustainability of an infrastructure project (Figure 3.9.). Each aspect is represented in a different colored box, with specific information describing the performance indicators or their impact, and it all comes down to one integrated end result. On the top left side, the Technical Aspects include a 15-year project design life and an annual maintenance cost of IDR 750 million, demonstrating a long-term commitment to reliability and infrastructure maintenance. To the right, the LCA highlights the long-term environmental impacts, such as 520 tonnes of CO_2 emissions and 20 years of infrastructure life, which are the basis for calculating LCC. In this example, the total cost over the life cycle of the project is $56.5 billion, with an initial cost of $42.5 billion—data that is important for budget planning and economic efficiency. From the economic side, the picture shows real benefits in the form of a 28% reduction in transportation costs and a 30% acceleration in logistics, which are the main indicators of economic efficiency and regional competitiveness. However, the evaluation does not stop here. At the bottom, Environmental Aspects considers ecological impacts, such as the area of affected forest (±1.2 hectares) and mitigation efforts through green drainage systems and reforestation—illustrating a commitment to ecological sustainability. Furthermore, the Social Aspect highlights benefits to communities, including reduced land conflicts and increased access to public services, reflecting equitable distribution of benefits and social justice. All of these elements are interconnected and contribute to the Holistic Evaluation Results, which are shown in a yellow circle in the middle: "Feasible, Efficient, Sustainable". It emphasizes that the success of modern infrastructure projects is not only measured by technical capabilities or economic benefits alone, but must meet environmental sustainability and social justice standards at the same time. This diagram serves as a strategic guide for planners and policymakers to make balanced and responsible decisions in a multidimensional manner.

The Holistic Approach Method for National Road Infrastructure Project Evaluation, begins with the determination of Multi-Dimensional Evaluation Objectives, through the determination of the scope of project evaluation by considering five main dimensions, namely 1) Technical, construction quality, material durability, maintenance; 2) Economy, influence on logistics, local economic growth; 3) Social, increased access, equality of public services; 4) Environment, conservation, land degradation, carbon emissions; 5) Finance, cost recovery, long-term maintenance efficiency. Second, the application of LCA and LCC, using LCA to assess the environmental impact of a project throughout its life cycle (from construction to demolition). Using LCC to calculate the total cost of a project in the long term including construction, maintenance, and rehabilitation costs [34]. Third, the integration of Digital Technology (BIM & BrIM). Implement BIM and BrIM to digitally model all physical and functional elements of the project. This facilitates including modeling of maintenance scenarios, visualization of traffic and environmental impacts, evaluation of operational efficiency and investment. Fourth, the measurement of Systemic Efficiency and Connectivity. Project evaluations based on systemic indicators such as reduced travel time, reduced logistics costs, and integration with existing ports, industrial estates, or road networks using real-time transportation data, logistics surveys, and macro transportation models to measure functional impact. Fifth, evaluation of Social Impact and Accessibility, by conducting qualitative and quantitative assessments of, including changes in people's access to education, health, and markets; influence on the mobility of vulnerable groups; social conflicts due to evictions or land clearing using participatory methods (FGD, surveys, interviews) with affected residents. Sixth, the Financial Sustainability assessment, by determining whether the project has a financing model that guarantees long-term maintenance, through Is there a special maintenance fund? Whether the toll model or regional contribution can cover operational costs? and whether the maintenance costs are by the region's fiscal capacity? Seventh, the preparation of the Integrated Evaluation Score can be done with an MCDM approach such as AHP or weighted scoring to combine all evaluation dimensions into a final score. Finally, the reporting of Policy Evaluations and Recommendations, with the results of the evaluation outlined in the report for stakeholders, such as the Directorate General of Highways, local governments, financing institutions, and affected communities. The report should recommend design improvements, maintenance policies, or replication to other projects.

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CHAPTER 4
ANALYSIS OF PAVEMENT CONDITIONS

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The condition of the road pavement is the main indicator in assessing the level of performance of land transportation infrastructure in an area. Roads that have pavements in good condition not only support the smooth flow of traffic, but also become a determining factor for economic efficiency, road user safety, and regional competitiveness in the context of national development. In Indonesia, as an archipelagic country with an extensive road network and diverse geotechnical characteristics, the analysis of pavement conditions is an important aspect of the road management system. Maintenance and improvement of the quality of roads on target requires accurate technical data as well as a systematic evaluative approach. Therefore, the study of the condition of road pavement is not only technical, but also strategic in supporting sustainable infrastructure development policies. Evaluation of road pavement conditions is generally carried out using quantitative indicators, one of which is the Pavement Condition Index (PCI). This index describes the level of road damage objectively and is the basis for determining maintenance and rehabilitation priorities. Through the PCI value, it can be known to what extent the performance of the road structure can still be maintained or requires structural repair. In addition, the results of the PCI evaluation are also important inputs in the formulation of road asset management policies at the national and regional levels. With this data-based approach, it is hoped that technical and administrative decisions in road management can be carried out more efficiently and in a more directed manner.

In a geographical context, Kalimantan is one of the regions with its own challenges in road construction and maintenance. The condition of the subsoil dominated by soft layers and high rainfall makes road pavements in this region vulnerable to premature damage. This requires the application of road engineering techniques that are adaptive to local natural conditions, as well as infrastructure management policies that pay attention to sustainability aspects. In addition to technical aspects, road conditions are also closely related to public policy and regional planning. Damaged roads will hinder mobility, reduce regional accessibility, and negatively impact the economic and social activities of the community. Therefore, the discussion in this chapter is directed to analyze the condition of road pavement from various perspectives, both technical and policy. The first subchapter discusses the results of the evaluation of the PCI on the national road network as the basis for assessing the condition of pavement. The second subchapter describes the condition of road pavements in the Kalimantan region based on geotechnical and environmental characteristics. Furthermore, the third subchapter explains the relationship between road conditions and public policy and regional planning oriented toward sustainable development. Finally, the fourth subchapter presents recommendations for improvement and road engineering strategies that can be applied to improve the performance of the national road network. Through this comprehensive analysis, it is hoped that a comprehensive picture of the actual condition of the road pavement and strategic steps can be taken for its improvement.

As a systematic basis for discussion, this chapter is prepared using a logical framing approach (as visualized in the image above). The framework of thinking connects technical aspects, regional characteristics, public policy implications, and integrated road engineering recommendations. This flow starts from the evaluation of road conditions using the PCI method, then continues with the analysis of environmental, material, and drainage factors that affect the level of damage. Furthermore, the relationship between road conditions and public policy was discussed, and ended with engineering recommendations and adaptive maintenance policies.

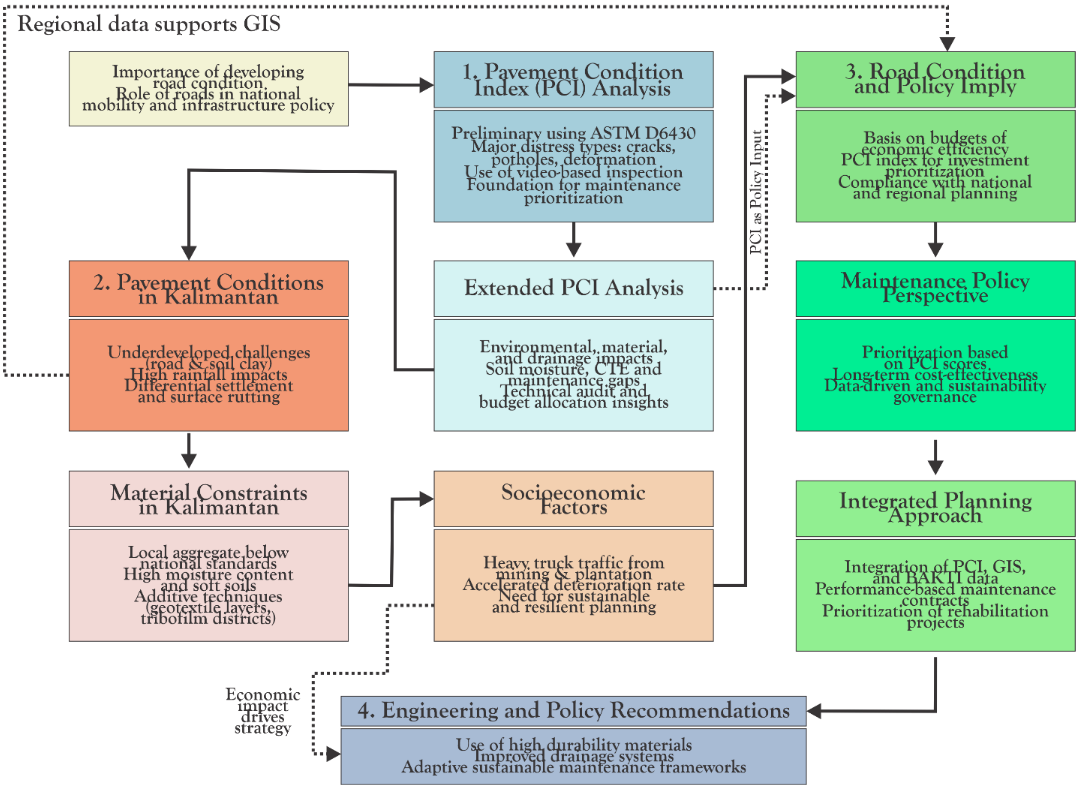

Figure 4.1. Analysis and Discussion of Road Pavement Conditions

Source: Author analysis, 2025

Within this frame of mind, there are four main domains of analysis that form the basis for the preparation of Chapter 4. First, PCI Evaluation and Analysis discusses the basis of the survey methodology, assessment of the type of damage, and factors that affect the variation in PCI values between regions. This analysis is used to understand the level of pavement damage objectively and serves as a reference in determining the priority of maintenance of the national road network. Second, the Road Pavement Condition in Kalimantan highlights the region's typical challenges with soft soil conditions, high rainfall, and limited aggregate materials that contribute to the acceleration of road damage. These geotechnical and environmental factors make the Kalimantan region an important study in the context of adapting road pavement technology in Indonesia. Third, the Relationship between road conditions, public policy and regional planning examines the two-way relationship between road pavement performance and government policies, both in budget allocation, investment priorities, and regional spatial planning. The results of the road condition evaluation are used as a basis for strategic decision-making to optimize infrastructure development and resource distribution. Fourth, the Engineering Engineering and Road Policy Recommendations formulate solutions based on the results of previous analysis, including the application of adaptive pavement technology, drainage system improvement, and GIS and IoT-based data integration to support efficient and sustainable management of national road assets.

Figure 4.1. shows sequential and interactive relationships between the parts. The blue block represents the technical evaluation stage in the form of PCI assessment and analysis, while the orange block represents the geotechnical and material challenges typical of the Kalimantan region. The green block explains the linkage between public policy and regional planning, while the last blue block contains recommendations for techniques and policies for systemic improvement. The dotted line indicates dynamic cross-topic relationships, such as how the results of the PCI evaluation can influence national policies or how socioeconomic conditions strengthen sustainable development strategies. Through this integrated analysis approach, Chapter 4 seeks to bridge the gap between technical diagnosis and road construction policy formulation. By combining the results of field evaluations, regional characteristics, and public policy contexts, the discussion in this chapter is expected to provide a comprehensive understanding of the actual condition of the national road network as well as the basis for an efficient, adaptive, and sustainable maintenance and rehabilitation strategy.

4.1 PCI Evaluation on the National Road Network

The evaluation of road pavement conditions using the PCI method is a recognized global approach in assessing the structural and functional performance of pavement. A study [1] shows that the application of PCI has grown rapidly as technology and road management policies have advanced in various countries, with evolutionary models now including Markov-based prediction systems and artificial intelligence. Another study [2] emphasized that modifications to the PCI method can improve the accuracy of the assessment of damage types such as cracks, holes, and surface deformations, where the deduct value curve approach results in a field fit rate of up to 90%.

In line with that, [3] developed a Gene Expression Programming (GEP)-based model to predict PCI values using the International Roughness Index (IRI) parameters, which have been shown to be able to explain up to 85% variation in pavement conditions with higher resource efficiency. A study in Iraq by [4] shows that regular PCI monitoring can identify decreased road performance due to strenuous activity, as well as that preventive maintenance measures can increase PCI values by up to 19%. Artificial intelligence-based approaches are also beginning to be integrated in PCI assessments. [5] research leveraged machine learning and Geographic Information Systems (GIS) to model the relationship between IRI and PCI, resulting in a faster and more accurate classification of road condition. In a similar context, [6] review deterministic, probabilistic, and machine learning-based pavement degradation models, highlighting that PCI remains the most effective indicator in modern pavement management systems. Furthermore, [7] evaluated the accuracy of PCI manual inspections using the ASTM D6433-23 standard, and found that technician training was able to improve the accuracy and consistency of survey results, which is critical to the validity of field data. Finally, a comparative study [8] shows that the deep learning model can predict a decrease in PCI values with an accuracy rate of up to 97.8%, outperforming conventional regression approaches.

The PCI survey methodology is generally carried out through visual inspection in the field of various types of pavement damage, such as cracks, holes, deformations, and grain removal, according to the guidelines of the ASTM D6433 standard. This process requires segmenting the path into assessment units with a certain area, then each unit is tested to calculate the deduction value against the total PCI. A study [9] outlined the implementation of a road maintenance management system in Iraq using Micro PAVER 7.0.8 software guided by ASTM D6433, where each 250 m^2 road segment was evaluated to determine the extent of structural and functional damage. This study shows the importance of dividing small segments so that the results of PCI are more representative of the actual condition. In the context of modernization of inspection methods, [10] introduced the SMART quality control analysis approach to improve the reliability of PCI survey data by using inter-rater reliability statistics such as Cohen's Kappa and Krippendorff's Alpha. This approach has been shown to reduce subjective errors in field assessments and improve data consistency between survey teams. Furthermore, [11] developed machine learning-based software capable of predicting PCI values by eliminating multiple recurring fault variables, thereby reducing the field inspection burden by up to 40% without sacrificing accuracy. Improving the efficiency of inspection methods is also studied through the use of imaging and sensor technology. [12] in a comprehensive review of computer vision-based automated inspection highlighted the alignment between two- and three-dimensional image detection systems with ASTM D6433-18 criteria, as well as the potential application of unmanned vehicles for road surface data acquisition. This technology complements traditional methods by allowing for rapid classification of different types of surface damage. [13] reinforced this relevance through the compilation of a dataset of pavement and climate conditions in Texas, United States, which showed that extreme weather factors such as flooding have a significant effect on the PCI value, so field data collection should be associated with environmental parameters.

In the context of the influence of traffic on variations in PCI values between regions, [14] examined the performance of Pyrolysis Carbon Black-modified asphalt mixture fields in Sri Lanka, showing that heavy traffic intensity accelerated PCI decline by up to 15% per three years on high-capacity sections. This study confirms that heavy traffic causes structural degradation faster than roads with light current. Similar results were obtained from the study of [15], which utilized drone LiDAR technology to monitor road conditions in Karawang, and found a significant match between drone-based 3D detection results and manual inspection with traditional PCI methods. These findings confirm that traditional visual methods are still relevant, but can be complemented by cutting-edge technologies to accelerate data acquisition and improve spatial accuracy. In addition, structural risk approaches also need to be taken into account in field surveys. [16] analyzed risk factors for instability on bridge pavements suggesting that the movement of reinforced concrete slabs in the transition area may indicate potential longitudinal cracking and local PCI degradation. This study emphasizes the importance of contextual observation of the road support structure in the PCI evaluation process. Overall, these studies show that field-based PCI survey methodologies continue to evolve toward evaluation systems that are more efficient, standardized, and adaptive to traffic and environmental conditions.

These new approaches are leading to the integration of digital technologies and analytics into PCI surveys. Field observation data taken by ASTM D6433 can now be processed with machine learning algorithms to identify fault patterns and estimate PCI value degradation over time. The system allows national road management agencies to map maintenance priority areas with a higher level of precision. With the support of big data and GIS, PCI variations between regions can be analyzed spatially to identify correlations between road conditions, traffic intensity, and climatic factors. The approach reinforces the argument that although the PCI survey method remains rooted in visual inspection, the integration of modern technologies provides a great opportunity to improve the accuracy and efficiency of road condition evaluations on a national as well as regional scale.

Follow-up analysis of the results of the PCI evaluation shows that environmental factors have a significant influence on the level of road pavement degradation. Extreme climatic conditions such as high rainfall, sudden temperature changes, and waterlogging can accelerate the fatigue process of asphalt materials and increase the risk of cracking and deformation. Research [17] tested the hydraulic performance of BlueLay drainage material as a water runoff control system in urban environments. The results showed that this material was able to reduce runoff by up to 100% at moderate rainfall intensity and 51% at extreme rainfall of 179 mm/h, proving the importance of an efficient drainage system in maintaining PCI values in humid climates. In line with these findings, [18] identified that clogging in porous asphalt is the main cause of decreased infiltration ability and acceleration of structural damage. The study emphasizes that clogging behavior at the micro scale is closely related to the efficiency of drainage systems and routine maintenance, where an inappropriate void design can degrade durability by up to 40% in five years. Thus, the condition of the drainage system is an important parameter in maintaining the PCI value, especially on roads with high rainfall. In addition to the hydrological aspect, the quality of construction materials is also a dominant factor. A comprehensive study [19] shows that shear strength and the bearing capacity of the sub-base layer greatly determine structural resistance to traffic loads and environmental loads. Through California Bearing Ratio (CBR) and Triaxial Compression testing, it was found that high-stability materials are able to extend the service life of pavement by up to 25%, as well as significantly reduce the annual PCI rate of decline. The quality of this foundation layer is directly related to the compaction process during construction, where density inhomogeneity has the potential to result in differential deformation in the top layer.

On the other hand, [20] underlined that temperature and humidity variations have a major effect on the performance of porous asphalt layers. Extreme temperature drops can cause cracking at low temperatures, while rising temperatures accelerate the asphalt oxidation process. The study also noted that the combination of modified asphalt and the use of fibers can improve grain release resistance (raveling) and slow down PCI degradation on high-traffic roads. In addition to thermal factors, the quality of asphalt materials is also affected by the mixture of additives used. [21] examined the performance of modified asphalt with waste rubber (crumb rubber) and recycled plastics under extreme weather conditions such as high temperatures and floods. The results showed that rubber-based asphalt had better resistance to oxidative aging, while recycled plastic asphalt showed faster degradation due to exposure to UV rays and extreme temperatures. These findings confirm the importance of selecting materials according to climatic conditions to maintain high

PCI values. The link between construction quality and PCI value was also strengthened [22] through ordinal logistic regression modeling on the N-55 National Road in Pakistan. This study found a direct relationship between the compaction density and the severity of damage such as rutting and pothole. Irregular compaction during the construction phase contributed to an average decrease in PCI values of 12 points over a five-year period. Thus, quality control at the construction stage is a crucial step to prevent premature degradation of pavement.

Meanwhile, the role of drainage systems is also associated with the sustainability of urban rainwater management. According to [23], runoff from poorly handled road surfaces have the potential to bring microplastics and chemical residues into water bodies. This study emphasizes the effectiveness of green infrastructure solutions such as bioretention systems and permeable pavements in reducing negative hydrological impacts while extending the service life of roads. These findings strengthen the argument that the PCI evaluation not only assesses the physical aspects of pavement, but also indicates the effectiveness of the urban drainage system that underpins it. From a macro perspective, [6] reviewed deterministic and probabilistic models of pavement performance degradation, and emphasized that environmental factors such as traffic load and thermal stress are the main determinants in the rate of PCI decline. The study highlights that the use of machine learning-based models can improve the accuracy of predicting road conditions by up to 90%, enabling governments to plan risk-based maintenance and budget efficiency. The PCI value is a multidimensional indicator that not only describes the condition of the road surface, but also the overall effectiveness of infrastructure management. Low PCI results often signal a combination of problems: ranging from poor material quality, inadequate drainage systems, to weaknesses in technical oversight during construction. Therefore, the interpretation of PCI values needs to be associated with environmental and operational variables to ensure targeted maintenance actions. Governments and road management agencies are advised to implement a technical audit system based on PCI data periodically so that infrastructure investment decisions can be directed to priority areas with the highest risk of degradation. With this approach, national road management is not only oriented toward physical improvements, but also on increasing the resilience of infrastructure to environmental and extreme climate pressures in the past

4.2 Road Pavement Conditions in Kalimantan

The condition of road pavements in Kalimantan has unique challenges that are greatly influenced by geotechnical factors and a humid tropical climate. The characteristics of the soil, which are dominated by soft soils such as peat and organic clay, make this region particularly vulnerable to differential degradation, cracking due to plastic deformation, as well as waterlogging that accelerates the deterioration of the surface layer. According to [24], an adequate geotechnical understanding should be supported by an subsurface conceptual model that includes the interaction between groundwater, pore pressure, and drainage systems. In Chapter 5 – Conceptual Models, the authors affirm the importance of hydrogeological analysis and three-dimensional modeling in road planning and maintenance in wet-climate areas. This approach allows for early identification of water-saturated zones that have the potential to lead to subsoil failure and degradation of pavement. In soil engineering, [25] examined the use of municipal solid waste incineration ash as a stabilization material for expansive clay soils. The test results show a significant increase in compressive strength and resilient modulus, as well as resistance to wet-dry cycles, making this technology relevant for tropical regions with high rainfall such as Borneo. Stabilizing soft soils with alternative materials has been proven to reduce surface subsidence by up to 40% compared to the use of conventional lime or cement, while reducing environmental impact.

The limited carrying capacity of peatlands in Kalimantan requires the application of cutting-edge geotechnical innovations. The book GeoVadis – The Future of Geotechnical Engineering [26] compiles research on soil strengthening, embankment, and dynamic stabilization in extreme climates. It is emphasized that the combination of geosynthetics with sensor-based monitoring systems can predict deformation and cracking before failure occurs. This approach is appropriate for the conditions of Kalimantan which has a thick soft soil layer and is saturated with water, where plastic deformation is often the main cause of the decline in road performance values. Empirical support for the importance of an integrated approach also appears in the publication Geotechnical Engineering Challenges to Meet Current and Emerging Needs of Society [27], which highlights that infrastructure in the Southeast Asian region requires adaptive design systems to geohazards such as landslides and erosion due to extreme rainfall. The report emphasizes that surface and groundwater management is a major factor in extending the life of pavements in the tropics.

In addition to natural geotechnical factors, the sustainability of construction in soft soil areas is also greatly influenced by the selection of materials and repair methods. Geosynthetics: Leading the Way to a Resilient Planet [28] presents evidence that the use of geotextiles and geomembranes can increase soil carrying capacity by up to two times by reducing vertical deformation. This book documents the application of a geogrid system on swamp access roads in Southeast Asia that can maintain road stability during two consecutive rainy seasons. Innovative approaches to dealing with the problem of low carrying capacity are also discussed in the volume Innovations for Sustainable and Resilient Infrastructure [29], which highlights the use of artificial intelligence and machine learning to predict the deformation behavior of soft soils. Through data-driven modeling, projects in Vietnam and the Philippines show that machine learning algorithms are able to estimate potential differential decline with up to 94% accuracy, so that maintenance programs can be planned preventively. On the material side, the research of [19] confirms that the geotechnical characteristics of the soil—especially the bearing capacity and shear strength—play a major role in the performance of the road foundation layer. Their study showed that increasing shear strength in organic clay soils through chemical stabilization can extend the service life of pavement by up to 25%, significantly reducing the need for routine maintenance. These results indicate that pavements in soft soils such as those in Borneo should be designed with dynamic structural capacity in mind, not just static parameters.

In addition to challenging natural conditions, a serious problem in road construction and maintenance in Kalimantan is the limited supply of quality construction materials. Widely used local aggregates often have low compressive strength, substandard wear resistance, and non-uniform grain distribution. According to [19], the bearing capacity of the subbase is highly dependent on the mechanical properties of the material tested through *the CBR* and *Triaxial Compression Test*. Materials with low shear strength will result in significant permanent deformation, accelerating the appearance of hair cracks and plastic deformation of the pavement layer. Therefore, testing the physical characteristics of local aggregates is a fundamental step before being used in the construction of national roads in Kalimantan. These challenges are exacerbated by humid tropical climatic conditions that cause extreme wet-dry cycles, resulting in high variations in humidity and pore pressure in the subsoil layer. A study by Ayesh Dushmantha and Gallage [30] introduced the concept of *the Degree-of-Saturation Threshold Decision Rule*, which is used to identify periods prone to damage during and after floods. The results of the study on granular-coated roads showed that when the water saturation level (DoS) exceeded 0.83, the stiffness of the layer decreased drastically and the risk of deformation increased by up to two times. This condition is particularly relevant for roads in Kalimantan, which often experience prolonged waterlogging due to high rainfall.

In addition to hydrological problems, soil geotechnical conditions in Kalimantan demand adaptation of pavement technology. The book GeoVadis – The Future of Geotechnical Engineering [26] highlights the importance of applying geotextile layers and geogrids in soft-land areas. This system can strengthen the bearing capacity of the subgrade layer by distributing the load laterally, reducing differential deformation, and extending the service life of the road by up to 40% compared to conventional pavement without reinforcement. This approach is particularly suitable for the conditions of Kalimantan which has layers of peat and organic clay with low carrying capacity. Geotextile technology is also discussed in depth in the volume Geosynthetics: Leading the Way to a Resilient Planet [28], which shows that the use of *geotextile reinforcement* on flexible pavement can reduce tensile strain in the base layer by up to 35% and improve load distribution on high-traffic intensity roads. Applications in tropical swamp areas in Southeast Asia show a significant reduction in surface cracking due to plastic deformation. Thus, the use of geotextiles is an effective technical solution in compensating for the weakness of low-quality local materials.

Furthermore, [24] in *Conceptual Models for Subsurface Engineering* affirm that conceptual modeling of subsurface soils is essential to understand the interaction between groundwater, aggregate layers, and drainage systems. This study shows that a well-designed subsurface drainage system can reduce pore pressure and improve the durability of pavement in low-bearing soils. The application of this geotechnical hydrological model is a reference in adaptive drainage planning for high-rainfall intensity areas such as Kalimantan. Aggregate quality issues are also studied in an international context. Pavement Systems Engineering [31] showcases the latest research on adaptive pavement systems for developing countries, including flexible pavement design strategies that take into account local aggregate quality variations. This book emphasizes the need to integrate *Los Angeles Abrasion* and *Aggregate Impact Value testing* in the material selection process to maintain the performance of the surface layer under repeated loads. This approach can be adapted to the Bornean context, where the availability of hard aggregates is very limited. The low quality of local materials also encourages the need for innovation in materials engineering. [25] show that ash from *municipal solid waste incineration ash* can be used as a stabilizing material for clay soil. The addition of 15% ash increases the compressive strength of the soil by up to 30% and lowers the plasticity, making it a viable alternative to construction materials in regions with limited aggregate availability. The use of local waste materials also supports the sustainability and cost efficiency aspects of the project.

Socio-economic factors have a significant influence on the performance and service life of road pavement, especially in areas with rapid growth in the industrial and mining sectors such as Kalimantan. Coal mining, palm oil, and plantation expansion have drastically increased the volume of heavy vehicles. Roads that were originally designed for moderate traffic loads now have to withstand axial loads that far exceed the design capacity. This accelerates the degradation of the pavement layer, characterized by an increase in the IRI value and the appearance of structural cracks in a short period of time. A study [32] in the Andes mountains shows a similar pattern, where an increase in heavy traffic load accelerates road damage by up to 27.9% per year, demanding an adaptive maintenance strategy based on the HDM-4 model to minimize long-term degradation. The link between heavy traffic pressure, extreme climate, and increased consumption of road materials was also shown in the study of [33] in Bangkok. Through a combination of the Highway Development and Management System-4 and material flow analysis, it was found that the increase in heavy traffic and annual flood cycles accelerated the consumption of road repair materials by up to three times between 2004 and 2022. This study shows a direct relationship between urban economic dynamics, climate pressures, and road infrastructure burdens. A similar phenomenon occurred in Kalimantan, where the combination of mining vehicles and extreme rainfall accelerated road surface wear and permanent deformation of the sublayer.

To support the long-term durability of roads in high-traffic load areas, pavement design must be supported by the right reinforcement materials and technologies. [34] developed a modified asphalt mixture with the addition of iron ore tailings (IOT) as a substitute fine aggregate. Compositions with 40% IOT showed an increase in compressive modulus of up to 203% and fatigue life of more than 1.6×10^7 cycles, equivalent to a 21-fold increase compared to the control mixture under heavy load conditions and extreme temperatures. Similar innovations can be applied in Kalimantan to improve resilience to overloads caused by mining trucks and plantation logistics. In addition to improving material quality, adaptive and participatory maintenance policies are an important element in the sustainability of road infrastructure. [35] through a study of the Provincial Road Improvement and Maintenance Program (PRIM) in West Lombok proved that the integration of engineering approaches and multi-stakeholder governance can reduce infrastructure lifecycle costs by up to 35% and increase public transparency. A similar approach can be applied in Kalimantan by involving the private sector and local communities in the monitoring and maintenance process, to improve the efficiency and accountability of road rehabilitation programs.

From the aspect of pavement materials, [36] in their review of modified asphalt highlight the importance of using additives such as polymers and crumb rubber to increase resistance to plastic deformation due to heavy loads. This technology allows for increased flexibility and stiffness of asphalt mixtures simultaneously, making them more resistant to rutting and cracking due to the influence of tropical temperatures and heavy vehicle loads. Considering the traffic conditions in Kalimantan, the use of asphalt modifications like this will be the right solution to extend the service life of national roads. In the context of strategic policy, [19] emphasized the importance of subbase evaluation using the CBR test and the Triaxial Compression Test to ensure stability and resistance to repetitive loads. The use of low-quality subbase materials without adequate strength tests may lead to premature deformation and cracking. Therefore, the application of laboratory-based technical standards is important for road improvement projects in heavy industrial areas. Efficient and sustainable road rehabilitation planning can also be improved with artificial intelligence technology. [37] developed a Deep Reinforcement Learning model to predictively determine the type and time of road maintenance based on the IRI and Rutting

Depth (RD) indicators. This model has been shown to be more efficient in budget and time allocation than conventional methods. The integration of predictive systems like this is important for Kalimantan, where traffic variations and extreme weather demand fast, data-driven maintenance decisions.

4.3 The Relationship of Road Conditions with Public Policy and Regional Planning

The condition of road pavement is directly related to public policy and regional planning strategy. In the global context, many studies confirm that the quality of road infrastructure is one of the main indicators of the success of a region's economic and social development. [38] developed the Territorial Infrastructure Support Index (ISIT) to measure the infrastructure gap between regions in Chile, and the results show that regions with good road infrastructure have higher economic attractiveness and productivity. In a study of transportation policy in the United States, [39] found that Metropolitan Planning Organizations (MPOs) use criteria such as safety, accessibility, environmental impact, and economic factors to determine the priorities of transportation projects, where road conditions play a key parameter in the assessment of investment needs. Assessment of pavement conditions is also an important tool in sustainable development planning. [40] propose a Holistic Impact Measurement (HIM) approach to assess the sustainability of transportation systems from three dimensions—economic, social, and environmental—that place the efficiency of road infrastructure as a key component in public cost optimization. Research [41] in Lithuania highlights the importance of scientific weighting in determining winter road maintenance levels, which can be used as a basis for national policies to reduce the risk of accidents and improve maintenance efficiency.

Meanwhile, a quantitative approach based on resource optimization was developed [42], who designed a clustering-based optimization framework to prioritize road projects based on fiscal constraints and socioeconomic impacts. This model has proven to be effective in balancing transportation needs with budget allocations in developing countries. On the other hand, [43] reviewed more than 2,600 publications on the application of the Analytic Hierarchy Process (AHP) in transportation decisions and concluded that this method is widely used by policymakers to assess infrastructure investment priorities based on actual road conditions and economic benefits. In the context of rural and mountainous areas, [32] combined the Highway Development and Management (HDM-4) model with AHP to optimize road maintenance in the Andean region, Peru. The results showed that the combination of these models improved the accuracy of rehabilitation planning by up to 20% compared to conventional approaches. In addition, Panahi et al. (2025) emphasize the need for data-based infrastructure planning to ensure the efficiency and sustainability of public investment, through a data-driven foresight approach that is also relevant in road and transportation management (DOI: 10.1016/j.jenvman.2025.126615). This study confirms that the condition of road pavement plays a role not only as a technical indicator, but also as a strategic element in regional development policies and infrastructure investment decision-making. The relationship between the PCI index, budget allocation, and economic efficiency is the basis for the formulation of sustainable transportation policies. A government that can integrate road condition data with regional economic planning will be more effective in creating connectivity and inclusive growth, especially in areas with high economic activity but infrastructure that is still lagging behind.

Public policy plays an important role in determining how design standards, materials, and road maintenance systems are applied consistently. When policies focus more on building new infrastructure without balancing the need for routine maintenance, the rate of road damage increases significantly, especially in tropical regions with heavy traffic. According to [44], the management of unplanned maintenance projects can reduce road capacity by up to 35% during the work period, which has an impact on congestion, high operational costs, and the acceleration of pavement degradation. Thus, policy-based planning that emphasizes preventive maintenance is key in maintaining the performance of the road network without sacrificing traffic and economic efficiency. Data-driven approaches to supporting maintenance policies have become common practice in many developed countries. The study of [45] in the Philippines shows that the integration of GIS systems in the evaluation of road conditions and traffic dynamics allows local governments to identify priority areas for improvement more accurately. This system provides a spatial classification of road conditions—from good to severely damaged—which is then used as a basis for the preparation of rehabilitation budgets and policies. The application of this kind of spatial technology at the provincial and national levels will increase the efficiency of the allocation of routine maintenance funds and reduce the inequality in the quality of the inter-regional road network.

Meanwhile, [32] combined the Highway Development and Management (HDM-4) model with the AHP method to determine the priority of road maintenance in the mountainous regions of Peru. This approach has improved the accuracy of rehabilitation planning by up to 20% compared to conventional methods, suggesting that the integration of optimization models and data-driven policies can provide more efficient outcomes for road systems with limited public funds. This strategy can be adapted in the Indonesian context, where the need for new roads often takes precedence over increasing the durability of existing roads. Governance models that are oriented toward public participation have also been shown to increase the effectiveness of road policies. The PRIM program studied [35] in West Lombok shows that the integration of technical approaches and multi-stakeholder governance can reduce life cycle costs by up to 35% compared to reactive systems. Through the establishment of a regional transportation communication forum (FLLAJ) and the implementation of the Anti-Corruption Action Plan, this policy has succeeded in creating transparency and accelerating the resolution of public complaints. This collaborative governance principle can serve as a model for public policy at the national level to improve the accountability of road maintenance systems.

In a technical context, policies that emphasize data-driven standards also strengthen the efficiency of regional planning. [6] review various models of predicting pavement damage in road management systems and highlight the importance of indicators such as the PCI, Pavement Surface Evaluation and Rating (PASER), and IRI as the main tools of national maintenance policies. When such indicators are integrated into public investment policies, the result is a more accurate prioritization between rehabilitation and new development. In addition, [46] emphasized that the application of artificial intelligence (AI) in transportation asset management can optimize decision-making regarding the time and type of maintenance required, by reducing reliance on manual inspections and improving the accuracy of predicting road damage. This technology opens up opportunities for evidence-based planning, where the condition of road pavement is one of the main parameters in the development of industrial, tourism, and residential areas. Preventive maintenance policies are also closely related to long-term cost efficiency. According to [47], the application of genetic algorithms and probabilistic models for maintenance planning in Cambodia can maximize the performance of the road network under limited budget constraints. This model considers varying wear levels based on pavement capacity and traffic load, resulting in a cost-effective multi-year intervention schedule. Optimization strategies like this are particularly relevant for developing countries that face a dilemma between the need for network expansion and the maintenance of existing infrastructure. From the perspective of regional planning, the integration of road condition data is a strategic instrument in determining the direction of regional development. Accurate data allows the government to identify ideal locations for the development of new industrial estates and settlements to connect with reliable road infrastructure. This is in line with the views of [38] who developed the Territorial Infrastructure Support Index (ISIT) to evaluate the relationship between infrastructure conditions and regional growth. The results of the study show that public investment directed based on the actual condition of the road network can accelerate the equitable distribution of development between regions.

The relationship between road conditions and public policy is two-way. Damaged or poorly maintained roads are not only an obstacle to people's mobility, but also interfere with the effectiveness of the implementation of public policies, such as the distribution of logistics of staples, education services, and health. According to [48], the effectiveness of road maintenance policies is highly dependent on data-driven decision-making systems, where indicators such as the PCI, IRI, and Average Annual Daily Traffic (AADT) are used to assess the cost efficiency and socio-economic impact of policies. This study shows that without management based on performance indicators, road investment is often inefficient and has a limited impact on people's welfare. An integrative approach that combines public policy with GIS has become a new foundation in regional planning. [32] developed a model based on Highway Development and Management (HDM-4) that is integrated with the AHP in Peru, combining traffic data, road surface conditions, and climate. The results show an increase in the accuracy of road rehabilitation planning by up to 18% compared to traditional methods, while providing priority guidance for local governments in infrastructure investment. Similar integration in Indonesia can support the development of integrated areas by considering the accessibility and resilience of the road network. The link between road conditions and sustainable development policies is also reflected in the concept of smart infrastructure. A book by Springer Nature [49], Highway of the Future: Transforming Mobility and Road Infrastructure, emphasizes that future cities and regions must integrate spatial data, traffic sensors, as well as AI algorithms in road management to support responsive policy planning. This approach allows for early detection of pavement damage and minimizes the social impact of transportation disruptions.

In addition to technological factors, socio-economic dynamics also affect the relationship between road conditions and public policies. Research [33] in Bangkok shows that increased heavy traffic and annual flooding events accelerate road damage by up to three-fold, while increasing the need for maintenance materials. The spatiotemporal analysis of material flow in the study highlights the importance of infrastructure policies that take into account climate and social factors simultaneously. This study strengthens the argument that road condition data is not just technical data, but also a tool to control the direction of public policy in the logistics and environmental sectors. The evaluation of road conditions also has a direct impact on decision-making related to the public budget. [50] examined the relationship between infrastructure condition data and road budget allocation at the local level using multiple regression and logistics. The results show that technical variables such as pavement deterioration and bridge condition significantly affect the distribution of funds, while data disintegration leads to inefficiencies in project prioritization. This shows that a GIS system that integrates PCI, IRI, and LHR data will be very useful in the formulation of more targeted and accountable fiscal policies. In policy risks, road conditions also play a role in strengthening infrastructure resilience to disasters. Research [51] in Chile shows that repeated flooding increases road user costs by up to 40% due to access disruptions and emergency repairs. By combining hydrological and traffic assignment models, the study confirms that development policies should incorporate hydrometeorological risks into road network planning so as not to hinder important public services.

Aspects of sustainability and urban mobility are also the focus of modern transportation policies. The book New Challenges for Sustainable Urban Mobility [52] states that the integration of road condition data with urban spatial policies is a crucial step to balance mobility, safety, and quality of life. This kind of policy emphasizes that a well-functioning transportation system should be seen as an instrument of regional development, not just physical infrastructure. Finally, [6] conclude that indicators such as PCI and IRI not only serve as technical measures, but can also be policy parameters in Pavement Management Systems (PMS) systems to assess the economic and social performance of road infrastructure. With a predictive approach based on machine learning, policymakers can determine the optimal time for treatment and assess the social impact of the deterioration of road conditions.

4.4 Recommendations for Improvement Based on Road Engineering Techniques

Based on the results of the evaluation of the condition of the pavement, repair recommendations can be prepared according to the level of damage identified. For roads with high PCI values (80–100), the recommended strategy is routine maintenance such as crack sealing, drainage channel cleaning, and surface layer rejuvenation. Roads with moderate PCI values (50–79) require light rehabilitation measures such as thin overlays using modified asphalt mixtures. Meanwhile, for roads with low PCI values (0–49), more significant structural improvements are required such as pavement layer reconstruction or partial replacement of the subsoil. Modern engineering approaches in road engineering now prioritize the concept of PMS, which integrates technical evaluation with data-driven decision-making. Technologies such as Ground Penetrating Radar (GPR) and Falling Weight Deflectometer (FWD) are used to assess subsurface conditions without having to carry out demolition. In addition, the use of innovative materials such as warm mix asphalt, recycled asphalt pavement (RAP), and soil stabilization with polymers is also an environmentally friendly and economical solution. In the context of Kalimantan and the national road network in general, engineering recommendations need to adapt to tropical climatic conditions and local soil characteristics. The implementation of an effective drainage system, strengthening the structure of the foundation layer, and monitoring the quality of materials are key factors for the success of repairs. In policy, it is important to implement a performance-based maintenance system so that contractors are encouraged to maintain road quality within a certain period of time. With the right technical and managerial approach, it is hoped that the condition of the national road network can be improved sustainably and provide optimal economic benefits.

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CHAPTER 5
REGIONAL PLANNING AND INFRASTRUCTURE DEVELOPMENT

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Regional development and infrastructure are two fundamental aspects that are interrelated in an effort to encourage national economic growth, improve community welfare, and create sustainable spatial planning. In the context of modern national development, regional planning is no longer understood solely as an effort to regulate physical space, but as a comprehensive strategy that includes social, economic, ecological, and institutional dimensions. Each region has different potentials, problems, and characteristics, so the regional planning strategy must be adaptive and evidence-based spatial planning. Infrastructure, as the backbone of development, is the main means of connecting the centers of human activity and expanding access to economic resources, social services, and employment opportunities. Therefore, the integration between regional planning and infrastructure development is the key to realizing inclusive, equitable and sustainable development. The first subchapter in this chapter, Regional Planning Strategies to Support Accessibility, discusses the importance of spatial planning strategies in creating inter-regional connectivity. Accessibility is the main indicator in assessing the extent to which a region can play a role in the national economic system. The regional planning approach is directed to reduce the gap between regions through the development of connectivity infrastructure such as roads, ports, and public transportation networks. In the era of globalization and digitalization, regional planning is also faced with new challenges such as rapid urbanization, climate change, and spatial inequality. Therefore, regional development strategies must emphasize the principles of sustainability, inclusivity, and resource efficiency. The development of multimodal transportation systems, the implementation of the TOD concept, and the use of information technology such as GIS are important elements in supporting accessibility

Furthermore, the second subchapter, Analysis of Road Service Levels Based on PM 96/2015, highlights the technical aspects of transportation management, particularly related to the performance of the road network as a vital element in the national mobility system. The Regulation of the Minister of Transportation Number PM 96 of 2015 is a reference in determining the LOS or the level of road service based on parameters such as traffic volume, free flow speed, and road capacity. LOS analysis not only serves to assess existing conditions, but also serves as a basis for decision-making in planning, engineering, and evaluation of transportation policies. In the urban context, the high volume of private vehicles and limited space encourage the need for innovative traffic management approaches, such as traffic demand management, one-way flow management, and the implementation of intelligent transport systems (ITS). Meanwhile, in non-urban areas, LOS analysis is more focused on the efficiency of the distribution of goods and services between regions. Thus, the policy of increasing the level of road services is an important instrument in supporting national connectivity and strengthening economic competitiveness between regions.

The third subchapter, Regional Planning Around the Capital City of the Archipelago (IKN), presents a concrete overview of the application of regional planning principles on a national scale. The relocation of the country's capital from Jakarta to East Kalimantan is a strategic step in creating a new growth center that is oriented toward sustainability, equitable development, and strengthening the integration of eastern Indonesia. This case study shows how the development of the IKN does not stand alone, but becomes part of regional planning involving buffer areas such as Balikpapan, Samarinda, and North Penajam Paser. The concept of green city and smart forest city is applied to ensure a balance between physical development and the preservation of tropical forest ecosystems. On the other hand, the development of connectivity infrastructure such as toll roads, ports, and public transportation systems is designed to form new economic corridors. In addition, strengthening governance through collaboration between the central government, regions, and the private sector is key in avoiding policy overlap and ensuring long-term sustainability. This study not only provides lessons for the development of the area around the IKN, but also serves as a reference for the practice of integrated regional planning in the future.

Finally, the fourth subchapter, The Impact of Infrastructure on Regional Economic Growth, discusses the close relationship between infrastructure development and increased regional productivity. Infrastructure acts as a catalyst in accelerating the flow of goods, services, and information, thereby lowering transaction costs and increasing economic efficiency. The construction of roads, ports, energy networks, and telecommunications has been proven to have a multiplier effect on economic growth, both at the local and national levels. However, these economic benefits can only be achieved if infrastructure development is accompanied by targeted and inclusive spatial planning. Inequality of access to infrastructure can deepen disparities between regions, especially between urban and rural areas. Therefore, a policy approach is needed that is not only growth-oriented, but also growth with equity. The integration between regional planning and infrastructure development enables the creation of a regional economic system that is resilient, adaptable to change, and globally competitive. Chapter 5 outlines the close interconnectedness between regional planning, infrastructure management, and economic development within the framework of sustainable development. Through adaptive spatial strategies, accurate technical analysis, implementable case studies, and an understanding of regional economic impacts, it is hoped that regional development approaches can be formulated that are not only economically efficient but also socially just and ecologically sustainable. Infrastructure development is not the final goal, but a means to create an inclusive, productive, and sustainable living space for all Indonesian people.

5.1. Regional Planning Strategies to Support Accessibility

Regional planning is a systematic process in regulating the use of space to achieve a balance between economic, social, and environmental development. One of the main goals of regional planning is to create equitable accessibility for all communities, both in urban and rural areas. Good accessibility is not only measured by physical distance, but also by the ease of the community in accessing various activity centers such as education, health, economy, and public services. In the context of regional development, accessibility is an important factor because it determines the extent to which an area can develop and integrate with other regions. A regional planning strategy to support accessibility must begin with an understanding of the existing conditions of an area. This includes geographical aspects, settlement patterns, transportation systems, and socio-economic characteristics of the population. With accurate mapping, the government can determine priorities for infrastructure development that can improve connectivity between regions. For example, the development of a network of main roads and connecting roads between sub-districts or villages that are adapted to local economic potential such as industrial, agricultural, and tourism areas. Thus, planning strategies are not uniform, but adaptive to the potential and needs of each region. Recent research confirms that spatial data-based mapping and transportation network analysis are key in building adaptive planning strategies. For example, a study in Malaysia assessed the efficiency of public transport networks using the General Transit Feed Specification (GTFS) and population density data, showing that the development of data-driven networks can improve the efficiency and equitable distribution of public access to public transport [1]. In addition, an integrative approach between connectivity planning and facility proximity is also important. Research in Greece shows that connectivity planning and proximity planning can together strengthen the accessibility of rural areas and reduce spatial inequality [2].

In urban contexts, accessibility is often associated with spatial planning and distribution of public facilities. Studies in Macau show that improved connectivity between roads and green open spaces can improve spatial integration and accessibility for all age groups, which has a direct impact on the quality of life of urban communities [3]. Similarly, research in China confirms that increased access to urban parks in the concept of a 15-minute living circle reinforces spatial justice and public health through ease of access for pedestrians and cyclists [4]. Furthermore, accessibility also plays a strategic role in economic equity and regional welfare. Studies in the Guangdong–Hong Kong–Macao Greater Bay Area region show that increased accessibility of high-speed rail networks can drive economic integration and reduce disparities between regions through improved mobility and spatial connectivity [5]. Similar findings in Johor Bahru and Penang, Malaysia, show that integration between modes of transportation and land use results in more efficient and spatially equitable transportation networks, so that they can be a reference in inclusive regional planning [1]. In addition to the physical aspect, the social dimension of accessibility also demands attention in regional planning policies. An international literature review on transportation equity emphasizes the importance of integrating social justice into transportation planning to ensure equal access for vulnerable groups and low-income communities [6]. This approach is in line with the principles of sustainable development that place spatial equality as the main cornerstone of regional planning. Thus, regional planning strategies should not be uniform, but should be adaptive to local potential and based on spatial evidence.

The development of multimodal transportation systems is an important strategy in modern regional planning to support accessibility, logistics efficiency, and sustainability. This system integrates various modes of transportation such as land, sea, and air to create an efficient and interconnected mobility network. Multimodal integration requires comprehensive planning so that there is no overlap of functions between modes and to ensure that connectivity between transportation nodes runs smoothly. Studies in Malaysia show that integrated terminals such as Larkin Sentral and Komtar Penang play an important role in the efficiency of transport networks and the improvement of regional connectivity [1]. The concept of TOD is also the main approach in supporting an efficient multimodal system. A study in Egypt shows that the implementation of TOD in the relocation of Helwan Metro Station improves connectivity between modes of transportation while reducing congestion and energy consumption in urban areas [7]. Similar results were found in Bengaluru, India, where the implementation of TOD on the Hebbal–Silk Board corridor has improved the quality of life of citizens by strengthening the integration between public transportation, pedestrian paths, and urban land use [8].

In addition to improving the efficiency of the movement of people and goods, an integrated multimodal system is also able to reduce logistics costs and travel time. The UK study emphasizes that avoid–shift–improve strategies in sustainable transport require cross-sectoral collaboration to integrate transport modes with spatial policies locally, thereby creating adaptive and sustainable mobility systems [9]. Research in Doha and Riyadh also shows that integration between TOD and public transport systems can strengthen connectivity between regions while optimizing land use in central business areas [10]. In the context of sustainability, the development of multimodal systems must consider their environmental and social impacts. The concept of green infrastructure plays an important role in minimizing carbon emissions, improving energy efficiency, and maintaining ecosystem balance. Studies in Europe show that transport planning integrated with green infrastructure can support the achievement of the European Green Deal target of reducing transport emissions by 90% by 2050 [11]. Meanwhile, research in Qatar shows that the application of the principles of walkability and green corridors in multimodal transportation planning improves air quality and urban public space comfort [12]. Furthermore, the inclusive planning strategy is an important pillar so that the development of multimodal transportation does not cause social inequality. A study in Thailand confirms the importance of the integration of a disability-friendly transportation system, with the result that an inclusively designed accessibility network can reduce travel time by up to 20% and improve the efficiency of public infrastructure [13].

The TOD approach is one of the regional planning strategies that focuses on developing areas around mass transportation nodes such as train stations, bus terminals, or BRT stop. The goal is to create a compact, integrated, and pedestrian-friendly environment, with an orientation toward easy access to public transportation. Through the implementation of TOD, economic activities, housing, and public facilities are concentrated in areas that are easily accessible by public transportation, thereby reducing dependence on private vehicles and reducing air pollution. A recent study in Bengaluru, India, showed that the implementation of TOD on the Hebbal–Silk Board corridor has succeeded in reducing travel time and improving the quality of life of urban communities by strengthening the integration of modes of transportation and land use [8]. Research in Riyadh, Saudi Arabia, also found that large investments in metro and BRT systems will only be effective if accompanied by spatial policies that support the concept of TOD, especially in increasing built-up density, pedestrian connectivity, and zoning policy synchronization [14].

Meanwhile, comparative studies in developing countries show that the success of TOD depends on supporting policy factors, transportation design, and proximity between facilities that are able to drive mobility efficiency and socio-economic well-being of communities [15]. The implementation of TOD also contributes to increasing urban resilience. A study in Taipei found that the spatial characteristics of TOD, such as high building density and accessibility to public transportation, are able to improve urban resilience to natural disasters such as typhoons and floods by strengthening connectivity and reducing infrastructure vulnerability [16]. In addition, a systemic analysis of urban regeneration projects in Europe shows that the success of sustainable urban transformation is determined by the integration between land use policies, transportation planning, and community participation mechanisms [17]. However, the success of TOD is determined not only by physical planning, but also by effective institutional governance and coordination. Research in Lahore, Pakistan, confirms that weak coordination between transportation and spatial planning agencies, as well as overlapping regulatory authority, are the main obstacles in the implementation of BRT-based TOD. The study recommends institutional reform, technical capacity building, and the establishment of incentive policies to encourage cross-sectoral collaboration [18]. A similar thing is found in the context of Jeddah, Saudi Arabia, where the integration of public transport policy and spatial planning is a key factor in realizing a low-carbon and inclusive urban mobility system [19]. Institutionally, TOD-based regional planning requires synchronization between spatial planning policies such as RTRW and RDTR and long-term transportation plans. The lack of coordination between agencies—such as transportation agencies, public works, and regional development planning agencies—can lead to mismatch in the direction of development and waste of resources. Therefore, adaptive, collaborative, and evidence-based governance is an important requirement in integrating the transportation system with regional development policies. This approach emphasizes that TOD-based planning is not just a physical project, but an integrated policy framework that connects aspects of mobility, sustainability, and regional governance.

The use of information technology is a key element in the strategy to increase regional accessibility in the digital era. The concept of smart city and spatial information system allows local governments to carry out data-based planning processes that are faster, more accurate, and more adaptive. Through GIS, the condition of the road network, congestion points, and infrastructure needs can be monitored in real-time, so that development policies can be prepared on an evidence-based basis. This approach has been shown to improve the effectiveness of regional governance as outlined in a comprehensive study [20], which highlights the application of geospatial technologies in building sustainable smart cities through spatial analysis and urban digital modeling. In addition, urban digital twins (UDTs) are an important innovation that enables dynamic simulation and visualization of cities to support public participation and more participatory decision-making. A systematic study [21] confirms that the implementation of UDT increases public perception of the built environment and advises public involvement in urban planning processes in various developed countries.

A case study in Egypt demonstrates the effectiveness of integrating GIS systems, artificial intelligence, and 5G networks in accelerating institutional coordination as well as improving equitable access to urban public services [22]. Digital transformation also opens up a wider space for community participation. [23] emphasized the importance of digital participation frameworks in supporting public participation in rural and mountainous areas, highlighting the challenges of digital inequality and the need to strengthen technology literacy as a prerequisite for inclusive participation. Similar findings are also shown [24], who affirm that participatory technologies such as citizen mapping and co-creation platforms are able to increase community collaboration in nature-based infrastructure projects in European cities. In the context of spatial management, the use of big data and social media analytics also provides new insights into the issue of infrastructure accessibility. A study [25] leveraged Twitter-based sentiment analysis integrated with GIS to identify road quality inequalities in East Java, showing how public participatory data can inform more responsive infrastructure policies.

On the other hand, spatial innovations such as the 15-minute city concept strengthen the connectivity between city functions through proximity-based spatial planning. A study [26] shows that this model can improve the quality of life of citizens while reinforcing the principle of accessibility and equitable distribution of public services in Portuguese cities. Through the application of geospatial technology, digital twins, and digital participatory frameworks, regional planning can now be done collaboratively between the government, academics, and the community. Synergy between spatial, social, economic, and institutional aspects is the key to creating equal and sustainable accessibility. With a technology-based approach and community participation, regional planning strategies not only improve mobility and connectivity efficiency, but also strengthen the social legitimacy of inclusive and resilient development.

5.2. Analysis of Road Service Level Based on PM 96/2015

The level of service or LOS is the main indicator in assessing the performance of road sections against traffic movements, including efficiency, comfort, and user safety. In the Indonesian context, the PM 96/2015 guideline regulates the LOS measurement method systematically based on parameters such as free flow speed, traffic volume, capacity, and degree of saturation. This approach is in line with global practice, where LOS evaluations are used as a basis for sustainable transportation planning and management. A study [27] confirms the importance of adjusting the Passenger Car Equivalent (PCE) value in heterogeneous traffic conditions to estimate road capacity more accurately in developing regions. In the context of developing countries, challenges such as high volume of heavy vehicles and congestion of road access reduce the performance of LOS. [28] identified the need for more infrastructure such as the construction of a third bridge in Bangladesh, after LOS measurements showed a significant decline due to the growth of industrial vehicles.

The study strengthens the argument that LOS assessments should take into account local socioeconomic conditions and regional industrial developments.

In addition, the development of empirical models is also a strategy to improve the accuracy of capacity and LOS predictions. [29] developed a multivariate regression-based empirical model to estimate the capacity of rural highway roundabouts in Bangladesh, taking into account geometric parameters and traffic flow. This model shows that variables such as lane width and volume of circulating vehicles have a significant influence on road capacity and service levels. The differences in traffic characteristics between developed and developing countries also demand adaptation in the LOS criteria. [30] developed a Three-Wheeler LOS (3W-LOS) prediction model using the Adaptive Neuro-Fuzzy Interface System (ANFIS) method for urban conditions in India, emphasizing the importance of considering non-conventional modes of transportation such as bajaj or three-wheeled vehicles in the assessment of LOS.

Furthermore, factors affecting mobility on open multilane roads are also an important focus. [31] found that access density and pedestrian activity were the most influential variables for speed reduction and increased degree of saturation on multilane roads in Pakistan. The research supports the importance of access control and pedestrian path arrangement in improving road performance. LOS analysis can also be attributed to environmental impact. A study [32] shows that the worst LOS (F) conditions at major intersections in Malang contribute to increased air pollution, especially NO levels that exceed thresholds. With the phase reset of traffic lights and vehicle flow, LOS performance and air quality can be improved simultaneously. In a methodological perspective, a data-driven approach to determining LOS criteria is also beginning to be adopted in developing countries. [33] used the K-mean clustering approach to assess the suitability of LOS criteria in urban arteries with irregular traffic flows in Karachi. The results showed that the velocity-appropriate volume-to-capacity ratio (V/C) for LOS A was about 0.45, suggesting that traditional LOS criteria need to be adapted to the local context.

The stage of road service level analysis (LOS) begins with the process of collecting traffic data which includes vehicle volume, average speed, and vehicle composition on each road. This approach is in line with international practice in analyzing road capacity and degree of saturation (DS) to assess the operational performance of the transportation network as a whole [34]. In an urban context, the DS calculation is used to determine whether a road section is still able to accommodate traffic growth or has entered a saturated state [35]. A DS value close to one indicates that conditions are almost saturated, while a value below 0.5 indicates that the traffic flow is still smooth. The use of technology in traffic analysis is now growing, such as the implementation of Automatic Traffic Counter and Sidra Intersection analysis software that facilitates the evaluation of service levels and traffic signal efficiency [36]. Recent studies also highlight the importance of artificial intelligence-based adaptive signaling systems that are able to adjust traffic light timing in real-time to improve the capacity and efficiency of intersections [37]. This approach is in line with the principles of traffic management and engineering (MRLL) in PM 96/2015 which emphasizes the efficiency of the use of existing infrastructure compared to the physical expansion of roads.

Several studies have shown that the application of signal timing optimization and traffic flow regulation can improve road network performance by up to 25% without the need for new construction [38]. On the other hand, the implementation of a real-time data-based traffic control system can also reduce vehicle delay time and energy consumption [37]. This technology-based and efficiency-based approach is in line with research findings in developing countries such as Nigeria, which uses neural networks to predict traffic vulnerability and determine the optimal capacity of urban roads [39]. In addition, the importance of integration between traffic data and transportation planning policies was also raised in recent research in the South Asia region that highlighted the close relationship between road geometry, vehicle volume, and transportation system reliability [38]. The stages of road service level analysis must be carried out comprehensively by combining empirical approaches, traffic engineering policies, and technological innovations. The principles of efficiency and sustainability set out in PM 96/2015 are consistent with international best practices that emphasize the optimization of road networks through real-time data and technology-based management strategies.

The analysis of the LOS not only assesses technical aspects such as the capacity and speed of traffic flow, but must also consider the safety and comfort of road users. Roads with high LOS are not necessarily safe if they are not supported by safety facilities such as sidewalks, road markings, lighting, and adequate traffic signs. The integration between LOS evaluation and road safety audits is crucial to ensure traffic performance improvements do not come at the expense of user safety [40]. The study in India emphasized the importance of institutional capacity building and training of road safety professionals so that transportation policies are not only oriented toward efficiency, but also on the reduction of fatal accidents. In the context of developing countries, transport policies that focus too much on motor vehicles often ignore the safety of non-motorized users such as pedestrians and cyclists. Studies in Namibia show that the lack of connectivity and facilities for non-motorized road users increases the risk of accidents and worsens the quality of urban mobility [41]. Similarly, research in East Africa shows that the quality of pedestrian infrastructure is directly proportional to the level of safety and comfort of road users [42].

PM 96/2015 is in line with international practice in balancing capacity, speed, and safety, and emphasizes traffic management as the main strategy in optimizing LOS without physical expansion of the road. A comparative study [43] shows that transport policies in India are starting to shift from a supply-oriented approach to demand-oriented, including the implementation of traffic demand management (TDM) such as restrictions on private vehicles and the promotion of public transport to control the level of saturation. The TDM approach has also received attention in a systematic study of urban regeneration that highlights the importance of integrating traffic policy with spatial planning and community participation. This integration results in safer and more efficient transportation without increasing emissions or access inequality [17]. Further, safety-oriented transport policy models are also implemented in small countries such as the Caribbean Islands, where sustainable transport development is geared toward reducing dependence on private vehicles and lowering transport costs [44]. The combination of TDM, road safety audits, and public transportation policies has proven to be effective in improving LOS on a sustainable basis. This is in line with the global paradigm toward an inclusive, safe, and low-carbon transportation system—a direction that is now also being pursued through the application of the PM 96/2015 principle in Indonesia. The analysis of the LOS in non-urban areas has a strategic role in maintaining the smooth distribution of goods and services between regions. National and provincial roads are the backbone of economic connectivity, so the decline in LOS can have a direct impact on logistics costs and regional productivity. A study [45] confirms that transport infrastructure has a direct relationship with rural economic growth, mainly through improved market access and supply chain efficiency. PM 96/2015 provides technical guidelines for evaluating the performance of arterial, collector, and freeway roads as a basis for capacity building through widening, construction of alternative routes, or pavement improvements. This principle is in line with the findings of [46], which highlight the importance of the sustainability of the national road network in ensuring the safe and efficient movement of goods and people across regions. Furthermore, an economic evaluation [47] shows that road development has in effect on increased investment and logistics efficiency, although it must be balanced with mitigation of environmental impacts through smart transportation systems and green infrastructure.

The development of information technology now allows real-time monitoring of road performance through ITS. The integration of ITS with the transportation decision-making system has been proven to improve traffic efficiency and road user safety. Studies in Ethiopia confirm that the adoption of ITS can improve inter-regional coordination and reduce the burden of fragmented policies in regional transportation management [48]. Similar results were put forward [49], who demonstrated the role of artificial intelligence (AI) in analyzing regional economic growth trends and transportation dynamics to support evidence-based planning. At the global level, the rural road network management strategy also emphasizes the importance of policy alignment between transportation and regional development. [50] highlight the direction of international transportation research that is now focused on the integration between logistics systems, public policies, and smart technologies to strengthen economic resilience and cross-regional connectivity. In the context of sustainability, rural road development also needs to consider the balance between logistics efficiency and socio-environmental impact. Thus, the application of PM 96/2015 in LOS analysis in non-urban areas is not only technical but also strategic—it is the basis for public investment planning, spatial planning, and data-driven transportation policies. The integration of technologies such as ITS and AI makes the evaluation process more accurate and adaptive to economic dynamics and the needs of rural communities, supporting the creation of an efficient, safe, and sustainable national transportation system.

5.3. Regional Planning Around National Capital City

The relocation of the National Capital City (IKN) to East Kalimantan reflects a new paradigm in national regional planning that prioritizes spatial integration, ecological sustainability, and equitable regional economic distribution. This approach is in line with international practice in which the development of the new capital is directed not only as an administrative center, but also as a driving force for the transformation of the surrounding region. In this context, the regional planning approach applied to the development of IKN is in line with the principles of eco-urbanization and smart green city as explained [51], that the integration between the digital economy and industrial ecology plays an important role in strengthening the sustainability of cities through the synergy of economic development and environmental protection. The application of the concept of green city in the development of IKN can also be attributed to a study [52], which highlights the importance of paying attention to local social and political aspects in the implementation of green urbanism to avoid social disparities due to speculative projects. In this case, the IKN planning strategy must ensure that physical development does not sacrifice the socio-ecological sustainability of local communities, especially communities around buffer areas such as North Penajam Paser and Kutai Kartanegara. In addition, regional planning around the IKN can also benefit from the digital-green fusion approach as outlined [53], which shows how digital technology can improve the management of urban natural resources such as urban forests to support ecological resilience and adaptive governance. This concept is in line with the vision of a smart forest city implemented in IKN, where GIS, environmental sensors, and digital monitoring are used to maintain the quality of Kalimantan's tropical forest ecosystem.

Furthermore, a study [54] emphasizes the importance of making smart and green city development a means to create cities that are socially inclusive and resilient to ecological stress, not just a technology project. This is relevant to the vision of IKN as a green and inclusive capital, which integrates spatial planning with the social needs of the community and ecological sustainability. From a land use perspective, [55] findings suggest that urban development in mountainous areas such as Shimla causes significant changes to land cover, resulting in biodiversity loss and increased environmental risks. Therefore, IKN planning needs to pay attention to land dynamics and ecosystem changes so as not to repeat the mistakes of uncontrolled urbanization as in this case. It is also important to review the social and spatial dimensions of urban development through an adaptive policy framework as recommended [56], which emphasizes the importance of using geospatial technologies in designing green infrastructure networks and climate change mitigation. The use of spatial data and geoinformatics analysis will strengthen evidence-based planning in the development of the IKN and its buffer areas. This approach is reinforced by a comparative study of green policies in East Asia put forward [57], which highlights the importance of the sustainability of green open space policies in the process of rapid urbanization as it occurred in Seoul. Thus, the IKN spatial planning policy needs to have a long-term vision in the management of public green space and sustainable infrastructure.

Regional planning around the IKN aims to create a buffer area that functions as a growth corridor based on sustainability and equity (Table 5.1.). This approach prioritizes spatial integration between the IKN and the surrounding area through an integrated transportation and spatial planning system. The intermediate objectives are directed at strengthening economic, social, and ecological connectivity between the core city and the hinterland region, while the outputs are focused on the provision of strategic infrastructure, spatial control, and green economic empowerment. Activities include the preparation of spatial planning documents, the construction of transportation networks, environmental rehabilitation, and cross-agency collaboration through public-private partnerships (PPP). With this logical framework, the development of the area around the IKN can be systematically monitored and evaluated based on measurable indicators (SMART) which include physical, social, economic, and environmental aspects. The use of spatial data and GIS is an important instrument in ensuring that the entire development process is by the principles of evidence-based planning and in line with the Sustainable Development Goals (SDG 11 and SDG 13).

The regional planning around the Nusantara Capital City (IKN) reflects a regional development approach that emphasizes spatial integration between the new government center and the buffer area. Through the IKN Master Plan and derivative documents such as the Detailed Spatial Plan (RDTR), the government developed a transportation connectivity strategy that included the construction of the Balikpapan-IKN toll road, logistics railway lines, and the modernization of supporting ports and airports (Table 5.1.).

Table 5.1. Regional Planning around the Capital City of Nusantara (IKN)

Hierarchy of Objectives	Indicators (SMART)	Means of Verification	Assumptions / Risks
Goal: To create a sustainable, inclusive, and resilient regional development system surrounding the IKN in East Kalimantan.	- Balanced growth between IKN and surrounding regions.- Reduction in spatial and economic disparities by ≥15% within 10 years.- 30% increase in regional GDP per capita (Kaltim region) within 2035.	- BPS regional statistics.- Annual reports from Otorita IKN.- Sustainable Development Progress Reports.	- Political and financial commitment from the central government remains stable.- No major environmental degradation.
Purpose: To integrate spatial, infrastructural, and socio-economic planning between IKN and surrounding regencies (Penajam Paser Utara, Kutai Kartanegara, Balikpapan, Samarinda).	- Completion of integrated RDTR for all buffer zones by 2028.- ≥80% alignment between regional and national planning documents.- Functional connectivity (toll, port, airport) by 2030.	- RDTR documents.- Infrastructure progress reports.- Evaluation by Ministry of ATR/BPN and Otorita IKN.	- Coordination between central and local governments remains effective.- Timely budget allocation and project execution.
Outputs: 1. Established regional infrastructure network.2. Clear spatial zoning and land use regulations.3. Strengthened local economy through green industries.4. Effective governance and monitoring systems.	- 200 km of strategic roads and one logistics rail line completed by 2030.- Land use plan approved and implemented in all buffer zones.- 25% of new industries apply green economy principles.- Functioning spatial data system for monitoring.	- Ministry of Public Works reports.- Environmental audit records.- Economic development performance indicators.	- Private sector participation is consistent.- Land acquisition processes are socially acceptable.- No significant delays in infrastructure development.
Activities: 1. Spatial mapping and zoning integration.2. Infrastructure masterplan preparation (road, port, airport, utilities).3. Local economic empowerment programs.4. Environmental management and restoration initiatives.5. Establishment of collaborative governance framework.	- ≥10 joint planning meetings per year.- 3 MoUs between central–regional authorities signed.- 5,000 workers trained in sustainable construction.- 2,000 ha of forest restored annually.	- Meeting reports.- Project documentation.- Environmental progress reports.- Labor and training statistics.	- Public support maintained.- Environmental permits approved on time.- Stable macroeconomic conditions.

Source: Author analysis, 2025

This strategy is in line with the eco-corridor model in the development of green industrial cities as described [58], which emphasizes the importance of integrating green spaces and slow-moving transportation systems to maintain ecological and social connectivity in metropolitan areas. From an infrastructure perspective, this improvement of the transportation network is an effort to strengthen regional economic corridors, which can lower logistics costs while expanding access between regions. The [47] study shows that the construction of highways and logistics lines has a direct effect on increasing investment and regional productivity, but it needs to be controlled so as not to cause urban sprawl and habitat fragmentation. In this context, the IKN strategy emphasizes the efficiency of the transportation network as well as environmental preservation through the implementation of green infrastructure.

In addition to transportation, the principle of balanced spatial allocation is also applied with a strict division of spatial functions between residential zones, sustainable agricultural areas, and light industrial areas. This approach is by the concept of harmonization of contact zones described [59], where the balance between dense urban areas and protected areas is key in preventing ecological degradation in buffer areas. The application of green and smart regional planning principles around the IKN can also be compared to similar projects in Asia such as NEOM in Saudi Arabia and Gelephu in Bhutan. A study [60] shows that the success of new cities is largely determined by the integration of economic, social, and environmental dimensions that are aligned with the local context. Therefore, the development of the area around the IKN must ensure the involvement of local communities and Kalimantan Forest conservation as part of a long-term sustainability strategy. Institutionally, this planning approach also reflects new political and governance dynamics as studied [61], which highlight the importance of evidence-based policies and public participation in the process of relocating the capital so as not to create inequality between regions. Thus, the development strategy of the area around the IKN can be an integrative model that combines economic development, environmental protection, and participatory governance. Regional planning around the IKN must also pay attention to the socio-economic dimension so that development is not only oriented to physical infrastructure, but also to the welfare of local communities. Increasing community capacity through education, training, and strengthening small and medium enterprises is an important foundation for inclusive development. As shown in a study [62], urban sustainability efforts need to balance aspects of distributive, economic, and environmental justice so as not to deepen social inequality. In addition, sustainable local economic development is an instrument to strengthen the resilience of communities to economic and demographic changes due to capital relocation, as described in the Center for Local Economic Development [63] which highlights the importance of sustainable infrastructure management in supporting regional development.

From an environmental perspective, the green economy and circular economy approach play an important role in maintaining the ecological balance of the IKN area. This concept is in line with the views of [64], who emphasizes the importance of integrating nature-based solutions and the circular economy in urban spatial planning policies to support long-term sustainability. The use of renewable energy and the implementation of zero-waste systems are key strategies in reducing the carbon impact of development. In addition, the concept of low-carbon city development as described in the Encyclopedia of the UN SDG: Sustainable Cities and Communities [65] is the theoretical foundation for the implementation of regional planning around the IKN to achieve inclusive, safe, resilient, and sustainable cities. Similar strategies are also being applied to other global regions that are transforming toward a green transition, as described [66], [67] in a study on local economic development in South Africa that emphasizes the importance of community participation and gender equality in supporting green economic development. Regional planning around the IKN reflects the application of the principle of inclusive green growth by integrating social, economic, and environmental policies in one integrated spatial framework. This also affirms the role of regional planning as a strategic instrument to achieve a balance between ecological conservation, community empowerment, and sustainable economic growth in the IKN area.

The governance of the area around the IKN is designed with a collaborative approach involving the central government, local governments, and the private sector within a multi-level governance framework. This approach is in line with global metropolitan governance practices as described [68], which emphasize the importance of cross-institutional coordination mechanisms and strengthening administrative capacity in integrated urban infrastructure planning. The role of the IKN Authority Agency is central as a coordinating institution that bridges national and local interests to ensure consistency in the direction of development and synchronization of spatial planning policies. Private sector involvement is also an important element in accelerating the development of basic infrastructure such as energy, clean water, and housing, which must remain in line with the principles of sustainability. In this context, [69] emphasizes the importance of green infrastructure planning based on cross-sectoral collaboration to achieve a balance between development and conservation, as seen in the Milan case study that incorporates socio-ecological aspects in regional spatial planning.

Furthermore, collaborative governance implemented around the IKN reflects the transition to smart governance, which utilizes spatial data and digital technology to improve the effectiveness of supervision and evaluation of development. [70] asserts that the implementation of smart city governance requires a holistic orchestration between actors, where technology serves as a link between governments, communities, and the private sector to create adaptive and participatory urban systems. This concept is also strengthened [71], who through a bibliometric analysis of 1,280 publications on urban governance, showed that collaboration between actors and institutional innovation is a key factor in the success of modern urban governance, especially in areas that are undergoing rapid transitions such as IKN buffer areas. From a social perspective, an inclusive approach is needed so that local communities can benefit directly from the development of the IKN. A study [72] shows that the transformation of marginalized areas into resilient urban centers requires participatory strategies that emphasize spatial justice and socio-economic integration of local citizens. This is relevant to the strategy of community empowerment in the area around the IKN through training programs, strengthening SMEs, and developing social infrastructure. [73] added that the success of smart city management in regions such as London, New York, and Barcelona is highly dependent on public involvement and policy transparency in PPPs. In the context of IKN, the PPP model plays an important role in ensuring the efficiency of development funding without sacrificing public accountability. The governance of the area around the IKN describes collaborative governance practices that are adaptive, data-based, and sustainability-oriented. If managed consistently, this approach will not only strengthen the economic competitiveness of the East Kalimantan region, but also make IKN an integrated regional development model that can balance economic, social, and ecological interests at the national level.

5.4. The Impact of Infrastructure on Regional Economic Growth

Infrastructure is one of the main pillars in the economic development of a region. The existence of adequate infrastructure — whether in the form of roads, ports, energy, clean water, and telecommunication networks — plays an important role in facilitating economic activities, increasing productivity, and encouraging equitable development. In the context of regional development, infrastructure functions not only as a physical facility, but also as a catalyst for regional economic growth. The relationship between infrastructure and economic growth is mutually reinforcing, good infrastructure development increases economic efficiency, while economic growth creates new demand for infrastructure. The impact of infrastructure on economic growth can be seen through several key mechanisms. First, infrastructure improves accessibility and connectivity between regions. The construction of roads, bridges, and ports allows the movement of goods and services to be faster and more efficient. This lowers logistics costs, expands market reach, and increases the competitiveness of local products. For example, the construction of the Trans-Java and Trans-Sumatra toll roads has been proven to significantly reduce the travel time of goods distribution, thereby encouraging the growth of the industrial and trade sectors in the surrounding area. At the regional level, increased accessibility also opens up new investment opportunities in previously isolated areas.

Second, infrastructure has a direct impact on labor absorption and community income growth. The construction of large infrastructure projects such as highways, dams, or airports creates a large number of jobs, both during the construction and operational phases. In addition, the existence of infrastructure advises the growth of derivative economic sectors such as construction services, trade, transportation, and tourism. This multiplier effect makes infrastructure an effective instrument in accelerating regional economic development, especially in areas that are still lagging behind. Third, infrastructure supports the development of new economic growth centers. The presence of transportation and energy infrastructure is often a trigger for the formation of industrial estates, logistics centers, or special economic zones (SEZs). With the availability of basic infrastructure, investors are more interested in investing in the region. For example, the development of the Mandalika and Bitung SEZs shows that infrastructure investment can transform areas with low economic potential into new productive activity centers. In this context, infrastructure acts as a strategic instrument in accelerating the transformation of the region's economic structure from natural resource-based to high-value-added industries and services.

However, infrastructure development must also be accompanied by integrated regional planning so that the economic benefits can be spread evenly. Without good planning, infrastructure can actually widen the gap between regions. Areas with complete infrastructure will grow faster, while areas with limited infrastructure are far behind. Therefore, the principle of balanced regional development needs to be applied through policies that encourage the distribution of infrastructure investment to areas that have potential but are still underdeveloped. The government needs to ensure that every infrastructure project has an inclusive economic impact and supports the equitable distribution of welfare. In addition, infrastructure also has a close relationship with the productivity of key economic sectors, such as agriculture, industry, and services. In the agricultural sector, the availability of irrigation, production roads, and crop storage facilities determine supply chain efficiency and price stability. In the industrial sector, energy and transportation infrastructure play a role in reducing production and distribution costs. Meanwhile, in the service sector, especially tourism and trade, infrastructure such as airports, ports, and telecommunications are the main requirements in attracting tourists and business actors. In other words, the quality and availability of infrastructure determine the economic competitiveness of a region in the domestic and global markets.

From a macroeconomic perspective, infrastructure investment has a large contribution to gross regional domestic product (GDP). Many studies show that increased public investment in the infrastructure sector can drive regional economic growth through increased labor productivity and production cost efficiency. For example, areas with high levels of infrastructure availability tend to have more stable GDP growth than areas with lagging infrastructure. However, it is also important to note that the economic benefits of infrastructure are not always immediate; In some cases, the positive impact is felt only a few years after the project is completed, especially if it is accompanied by supporting policies such as investment incentives and human resource development. In the context of sustainable development, infrastructure development must consider environmental and social aspects. Large-scale infrastructure development often carries risks such as ecosystem damage, land use changes, and population displacement. Therefore, every project needs to go through an environmental impact analysis (EIA) and involve the participation of local communities in the planning process. The concept of green infrastructure is now increasingly applied, where physical development is carried out by paying attention to energy efficiency, water conservation, and the use of environmentally friendly materials. This approach not only maintains ecological balance but also increases the resilience of the region to climate change.

Furthermore, the role of local governments and fiscal policy is a key factor in maximizing the impact of infrastructure on regional economic growth. Local governments must be able to identify priority infrastructure needs according to the economic potential of their regions, as well as establish partnerships with the private sector through the PPP scheme. Alternative funding such as regional bonds or creative financing can also be a solution to accelerate development without relying entirely on the central budget. The success of infrastructure development will depend on the ability of the regions to manage resources, manage spatial planning, and optimize local economic potential. Infrastructure is not just a symbol of physical progress, but also a key foundation for sustainable and inclusive economic development. Well-planned and managed infrastructure will create connectivity, increase economic efficiency, strengthen regional competitiveness, and accelerate the equitable distribution of national welfare. Therefore, infrastructure development must be placed as a long-term investment that is directed and based on the real needs of the community. Regional economic growth can develop dynamically, equitably, and sustainably.

Regional planning and infrastructure development are closely related in realizing sustainable, inclusive, and competitive national development. This chapter has outlined that adaptive, data-driven, and accessibility-oriented regional planning strategies are the key foundations for equitable development between regions. Through a comprehensive spatial approach, the government can identify the potential and constraints in each region so that the direction of development becomes more directed and efficient. Good accessibility has been proven to be able to strengthen connectivity, expand the reach of public services, and improve the quality of life of people at various levels. The integration of multimodal transportation systems and the application of the TOD concept is clear evidence of how spatial planning can promote mobility efficiency and reduce pressure on the environment.

The analysis of the level of road services as stipulated in PM 96/2015 shows the importance of managing transportation infrastructure based on actual performance and capacity. The level of service Evaluation (LOS) is not only a technical tool, but also serves as a policy basis in regulating traffic and determining infrastructure development priorities. The application of traffic management and engineering principles (MRLL), the use of ITS, and the implementation of TDM policies emphasizes the need for innovative and efficient approaches in facing the challenges of urbanization and increased mobility. In non-urban areas, LOS analysis helps to maintain the smooth distribution of goods and services that have a direct impact on regional economic productivity. A case study of regional development around the IKN shows the real implementation of integrated regional planning. The development of the IKN is not only a project to relocate the center of government, but also a spatial and economic transformation on a national scale. The green city and smart forest city approaches implemented demonstrate a commitment to ecological sustainability, while the development of economic corridors and connectivity infrastructure underscores the importance of a balance between development and conservation. Collaborative governance between the central government, local governments, and the private sector reflects a multi-level governance model that can serve as a reference for other regional development projects in Indonesia. In this context, the area around the IKN has the potential to become the epicenter of new economic growth that strengthens the integration of the eastern region of Indonesia.

Finally, the discussion on the impact of infrastructure on regional economic growth emphasized that infrastructure investment is not only a physical activity, but a long-term economic strategy. Infrastructure functions as the main driver of regional growth because it can reduce logistics costs, improve connectivity, and open up new economic opportunities. However, the benefits of infrastructure will be optimal if it is accompanied by inclusive spatial planning and policies that pay attention to equity and sustainability. Therefore, infrastructure development needs to be directed not only at increasing physical capacity, but also at creating social and environmental values that support community welfare. Overall, Chapter 5 emphasizes that the success of regional and infrastructure development in Indonesia depends on the synergy between spatial, technical, social, economic, and institutional aspects. Integrated, evidence-based planning will ensure that any development policy aligns with the SDGs, especially in sustainable cities and communities, industrial infrastructure, and the reduction of regional inequality. Thus, the direction of Indonesia's regional development in the future must be oriented toward a balance between economic growth, social justice, and environmental sustainability, to create a resilient, productive, and just living space for all Indonesian people.

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CHAPTER 6
PUBLIC POLICY IN INFRASTRUCTURE MANAGEMENT

Infrastructure is the backbone of a country's economic and social development. Without adequate infrastructure, inter-regional connectivity will be hampered, logistics costs will increase, and national economic growth will be difficult to develop evenly. Therefore, infrastructure management is one of the main focuses of public policy in Indonesia. The government has a central role in formulating, implementing, and evaluating policies related to infrastructure development and maintenance, especially in the land transportation sector which includes national road networks, toll roads, and urban traffic systems. Public policy in the field of infrastructure does not only talk about physical development, but also involves aspects of governance, funding, regulation, and synergy between sectors. In this context, the government is expected to be able to implement policies that are responsive to the needs of the community and adaptive to social, economic, and technological changes. The development of the national road network, handling congestion in urban areas, and data-based policy evaluation are concrete examples of the government's efforts to realize an efficient and sustainable transportation system.

Furthermore, the success of public policies in the infrastructure sector cannot be separated from collaboration between the central government, local governments, the private sector, and the community. This synergy is needed to ensure that the policies implemented are not only oriented toward achieving physical development targets, but also on improving the quality of life of the community and equitable distribution of development results. This chapter will discuss four main aspects of public policy related to infrastructure management, namely: government policies in the development of national road networks; implementation of public policies to overcome congestion; evaluation of data-driven policies such as Volume Capacity Ratio (VCR) and travel speed; as well as synergy between public policy and transportation engineering. These four aspects are interrelated in creating a resilient, efficient, and equitable infrastructure system for all regions of Indonesia.

6.1. Government Policy in the Development of the National Road Network

The development of the national road network is one of the government's strategic priorities in supporting economic growth, equitable distribution of regional development, and improving connectivity between regions. National roads serve as the lifeblood of transportation that connects production, distribution, and consumption centers throughout Indonesia. The government, through the Ministry of Public Works and Public Housing (PUPR), plays the role of the main policy maker that regulates the planning, development, maintenance, and evaluation of all national road infrastructure. This policy is regulated through various legal instruments, such as Law Number 38 of 2004 concerning roads, as well as various derivative regulations that regulate the authority and division of responsibilities between the central and regional governments. In the context of planning, government policies are focused on the principles of efficiency, effectiveness, and sustainability. The preparation of the National Road Network General Plan (RUJRN) is the main basis for determining development priorities. This planning process involves analyzing traffic needs, geographical conditions, and the economic potential of the area through which the road network passes. The government also applies data- and technology-based approaches, such as digital mapping, geographic information systems (GIS), and transportation models to determine the most technically and economically optimal routes. This approach is important to ensure that road construction not only meets current needs, but is also able to anticipate future mobility growth. In line with international practice, various studies show that the construction of a national road network designed in an integrated manner has a significant impact on economic productivity and inter-regional connectivity. For example, an analysis [1] shows that investment in the main road network contributes to increased regional productivity and more efficient logistics distribution. Meanwhile, research [2] confirms that the quality of road infrastructure planning is directly related to the sustainability of the national transportation system, especially in the context of developing countries. Furthermore, research from [3] highlights the importance of integration between public policy and transportation engineering to support infrastructure development that is adaptive to climate change and population growth. In addition, [4] emphasized that data-driven planning through the use of GIS and big data analytics can optimize road networks more effectively than traditional methods.

In the context of financing and collaboration, a study [5] shows that partnerships between the public and private sectors can improve the efficiency of national road infrastructure development, provided they are accompanied by transparent and performance-based governance. In line with that, the results of research conducted by [6] found that directed public investment in strategic road networks has a multiplier effect on the local economy, especially in remote areas. Furthermore, the sustainability approach is also an important dimension in national road planning. Research [7] emphasizes the need for transportation policies that are oriented toward environmental and social impacts, including emission reduction and road user safety. In addition, a study by [8] shows that the effectiveness of national road construction can be significantly improved if policies are integrated with data-driven evaluation systems and infrastructure performance indicators.

By adopting data-driven policy practices and learning from international experience, the Indonesian government can strengthen the effectiveness of national road network development policies. Synergy between technical, institutional, and adaptive public policy aspects is key to ensuring that infrastructure development is not only oriented toward improving connectivity, but also on economic, social, and environmental sustainability in the long term.

In addition to technical planning, the financing aspect is an important element in the national road network development policy. The government not only relies on the State Revenue and Expenditure Budget (APBN), but also optimizes alternative financing schemes such as Government Cooperation with Business Entities (PPP). The scheme allows for the participation of the private sector in the construction and management of toll and non-toll road infrastructure, with the principle of proportionate sharing of risks and benefits. This model is in line with global practice, where Public-Private Partnerships (PPPs) are an important instrument to overcome government fiscal constraints and improve the efficiency of infrastructure projects. A study [9] confirms that PPP can accelerate the realization of strategic transportation projects when accompanied by transparent and performance-based governance. In addition to financial efficiency, transparency and fair risk sharing are determining factors for the success of PPP schemes. [10] highlight the importance of independent monitoring and evaluation mechanisms to ensure that national road projects financed by the private sector not only benefit investors, but also provide social value for the public. Furthermore, [11] show that the success of the PPP model is highly dependent on the stability of public policy and the clarity of the regulatory framework in the sharing of responsibilities between the government and the private sector. In the Indonesian context, this approach is relevant given the need to accelerate infrastructure development amid the country's considerable fiscal limitations.

The policy of building the national road network must also pay attention to environmental and social aspects. Each project must go through the Environmental Impact Analysis (EIA) process and public consultation so that its implementation does not cause losses to the surrounding community. A similar approach is applied internationally. [12] found that integration between infrastructure planning and environmental policy can reduce social conflict as well as strengthen project legitimacy. [13] added that environmental impact evaluations carried out from the project design stage can reduce mitigation costs at the construction and operational stages. In addition to the environmental aspect, the involvement of local communities is an important dimension in realizing the success of the national road project. [14] assert that public participation in the infrastructure planning process increases people's sense of ownership of projects, while minimizing social resistance. This participation also supports the collection of more accurate socio-economic data to determine compensation and equitable relocation policies. On the other hand, [15] show that collaboration between actors—government, private, and community—can strengthen accountability and accelerate the completion of large infrastructure projects. The road infrastructure financing policy is also directed to strengthen the competitiveness of the national economy. According to [5], increased connectivity through national road investment directly contributes to regional productivity and reduced logistics costs. This is in line with research [16] which shows that planned land transportation investments can increase regional equity and long-term economic growth through increased interregional accessibility. With policies based on efficiency, collaboration, and sustainability, the construction of national roads is expected to not only be a means of transportation, but also a driving force for economic growth and equitable distribution of development between regions. The challenge ahead lies in the government's ability to maintain a balance between accelerating development, environmental management, and financing efficiency. As emphasized [17], the integration of fiscal policy, financing innovation, and sustainable approaches is an important foundation in creating a resilient and inclusive national road infrastructure system.

6.2. Implementation of Public Policies to Overcome Congestion

Traffic congestion is one of the complex problems faced by almost all major cities in Indonesia. The growth in the number of vehicles that is not proportional to the capacity of the road, the increase in population mobility, and the weak integration of the public transportation system are the main causes of chronic congestion. This problem not only reduces travel time efficiency, but also has an impact on economic productivity and the quality of the urban environment. Similar phenomena also occur in various major cities of the world, where rapid urbanization and economic growth are not balanced by adequate transportation infrastructure capacity. [18] showed that increasing vehicle density in urban centers without adaptive spatial planning can reduce transportation efficiency by up to 30%. In this context, the implementation of public policy plays an important role as a strategic instrument of the government in regulating, controlling, and managing traffic flows to create efficiency in people's movements and smooth distribution of goods and services. The implementation of the policy is not only oriented toward reducing the volume of vehicles on the highway, but also on transforming people's behavior in using more sustainable modes of transportation. According to [19], an effective congestion management strategy must incorporate aspects of policy, technology, and change in road user behavior to achieve long-term impacts.

The Government of Indonesia has adopted various policy approaches to address congestion in urban areas. One of the most significant steps is the development of integrated mass transportation systems such as Bus Rapid Transit (BRT), Mass Rapid Transit (MRT), and Light Rail Transit (LRT). The implementation of this policy is in line with the global experience. A study [20] shows that the development of BRT systems in developing cities can reduce the volume of private vehicles by up to 25% and improve the efficiency of urban travel. In addition, [21] affirmed the importance of intermodal integration in improving the efficiency of urban mobility and strengthening the attractiveness of public transportation. Intermodal integration through the construction of transportation nodes connecting trains, buses, and nonmotorized transportation has proven to be effective in reducing travel time and optimizing urban transportation networks. In international practice, this approach is known as the Transit-Oriented Development (TOD) policy which emphasizes the development of urban areas based on public transportation. The implementation of public transportation policies cannot be separated from the social and behavioral aspects of the community. [22] emphasize that the success of sustainable mobility policies is strongly influenced by the level of public acceptance of changes in travel patterns. In the context of developing countries, policy support in the form of fare incentives and improving the comfort of public transportation is the key to changing people's behavior. [23] added that private vehicle control policies must be balanced with improving the quality of public services so that people are encouraged to switch to mass transportation modes.

In technology policy, the use of intelligent transportation systems or Intelligent Transportation Systems (ITS) is one of the important innovations in modern traffic management. [24] affirm that ITS implementations, such as adaptive traffic signal settings and big data-driven traffic sensors, can improve vehicle flow efficiency by up to 20%. Meanwhile, [25] identified that the use of artificial intelligence for real-time congestion analysis can strengthen the effectiveness of urban transportation management policies. This policy approach reflects the government's efforts to build a planned and environmentally friendly urban mobility system, by the principles of sustainable development. [26] in their latest study showed that cities that successfully overcome congestion in a sustainable manner have the characteristics of integrated policies between spatial planning, public transportation, and road user behavior. Therefore, the success of congestion control policies is determined not only by physical infrastructure, but also by the synergy between public policy, technology, and community participation in creating an efficient and humane mobility system.

In addition to the development of public transportation infrastructure, the government also implements traffic management policies based on regulations and technology to reduce the level of congestion in urban areas. One example of implementation is the odd-even system in DKI Jakarta, which aims to limit the use of private vehicles during peak hours and encourage people to switch to public transportation. This approach to restricting vehicles is widely adopted in major cities around the world, such as Beijing, London, and Mexico City, with varying effectiveness depending on the consistency of policy implementation. [27] emphasized that road pricing policies and restrictions on private vehicles have proven to be effective in reducing congestion by up to 15–25% when combined with improving the quality of public transportation. On the other hand, the application of ITS technology such as surveillance cameras, traffic sensors, and adaptive traffic signal settings is an important innovation in improving the efficiency of vehicle flow management. ITS plays a role in collecting traffic data in real-time, which is used to support fast and evidence-based decision-making. According to [24], the implementation of a big data-based adaptive traffic control system can reduce vehicle delay times by up to 20% in large city centers. Similarly, [25] show that the implementation of ITS integrated with public transportation systems can improve the reliability of transportation networks and reduce fuel consumption.

Technology-based policies also strengthen traffic law supervision and enforcement systems. A study [28] found that the use of automated cameras and license plate recognition technology can increase road users' compliance with traffic regulations, especially in high-traffic areas. In Europe, machine learning-based intelligent traffic management systems have also been used to optimize traffic light patterns adaptively to real-time road conditions [29]. However, the implementation of public policies to overcome congestion is inseparable from various structural challenges. One of the main obstacles is coordination across institutions and levels of government that is not optimal. According to [30], synchronization between national and regional policies often leads to inefficient resource allocation and overlapping authority in urban transportation management. [31] [32] added that the difference in priorities between central and local governments is an obstacle in the implementation of sustainable transportation policies in various developing countries.

In addition, budget limitations for the development of public transportation infrastructure are also the main inhibiting factors. [33] show that fiscal constraints of local governments often slow down the modernization of transportation systems, so collaboration with the private sector is crucial to ensure the sustainability of infrastructure investments. In this context, PPPs function as an effective alternative financing instrument, as explained [34] that the PPP model can accelerate the development and maintenance of urban transportation when implemented with transparent and performance-based governance. Private sector involvement not only strengthens financing capacity, but also advises innovation in transportation operations through the adoption of new technologies and digitalized systems. [35] emphasize that collaboration between governments and transportation technology companies can accelerate the adoption of ITSs and improve the overall user experience. Therefore, cross-sectoral collaboration and intergovernmental policy synergy are the main foundations in realizing adaptive, efficient, and sustainable urban traffic management amid the complexity of modern mobility.

Social and cultural factors of the community have a huge influence on the effectiveness of the implementation of public policies in the transportation sector. Low public awareness of switching to public transport and a strong preference for private vehicles are often the main obstacles to reducing congestion. [36] emphasized that people's mobility behavior is strongly influenced by social norms and perceptions of social status attached to private vehicle ownership. In many developing countries, private vehicles are still seen as a symbol of economic progress and convenience, so changing transportation behavior requires a persuasive and sustainable public communication strategy. To overcome these challenges, the government needs to take an educational and persuasive approach through public campaigns, socialization, and incentives so that people are encouraged to use public transportation. [37] explained that incentive policies such as fare subsidies, intermodal fare integration, and the provision of park and ride facilities are able to increase the attractiveness of public transportation by up to 30% in metropolitan areas. On the other hand, [38] found that improving the comfort, safety, and punctuality of public transportation are key success factors in driving changes in people's travel behavior.

The government can also strengthen the strategy through more comprehensive spatial planning. [39] affirm that the integration between transportation policy and land use contributes significantly to the reduction of daily travel distances and dependence on private motor vehicles. The TOD approach is one of the effective long-term strategies to reduce congestion and create sustainable mobility patterns. Through TOD, residential, commercial, and office areas are integrated with direct access to public transportation nodes. A study [40] showed that the implementation of TOD in Lisbon and Stockholm managed to reduce the use of private cars by up to 20%. In addition, land use control and building density regulation are important aspects in supporting sustainable mobility policies. [41] show that policies restricting development in traffic-congested areas can reduce pressure on the road network and improve the efficiency of the city's transportation system. Meanwhile, [42] added that the development of urban planning based on public transportation integration can strengthen social cohesion and significantly reduce transportation carbon emissions. The implementation of public policies to overcome congestion requires synergy between physical, regulatory, social, and technological aspects. [43] emphasized that sustainable mobility policies can only succeed if they are based on inter-sector coordination and active community involvement in planning. The government also needs to ensure that any transportation policy is based on accurate data, periodic evaluation, and consistent oversight. The evidence-based policy approach outlined shows that real-time data-driven analysis helps increase the effectiveness of urban transportation policies in Turkey compared to traditional approaches. With the synergy between the right regulations, changes in people's behavior, and the support of technology and spatial planning, public policies in the transportation sector can be an effective instrument to create an orderly, efficient, and highly competitive traffic system at the global level. As revealed [44], the success of transportation policies is not only measured by the reduction in the volume of vehicles, but also by the improvement of the quality of life, social mobility, and overall well-being of the community.

6.3. Data-Driven Policy Evaluation for VCR and Travelability

Data-driven public policy evaluation is an important step in ensuring the effectiveness and efficiency of policy implementation, especially in the transportation and road infrastructure sectors. In the context of traffic and congestion management, the government needs objective and measurable measurement tools to assess the extent to which the policies implemented have succeeded in achieving their goals. This data-driven approach allows for more transparent decision-making and is adaptive to the dynamics of the field. [45] affirm that effective transportation policies depend on a monitoring and evaluation system based on measurable performance indicators, not just the results of policy perceptions or assumptions. One of the commonly used approaches in traffic policy evaluation is the analysis of VCR and average travel speed. These two indicators provide a quantitative picture of road performance conditions and traffic service levels, which can be the basis for planning, implementing, and improving transportation policies. [46] show that the systematic use of VCRs can improve accuracy in prioritizing infrastructure investments and assessing policy impacts on urban traffic performance. VCR is the ratio between the volume of vehicles crossing a road and the maximum capacity of the road. The VCR value provides an indication of the extent to which the road can accommodate traffic flow optimally. The higher the VCR value (close to or exceeding 1.0), the greater the level of congestion and potential congestion on the road. [47] underline that VCR values can be used as a key parameter in assessing the effectiveness of traffic control policies and in transportation model-based policy simulations.

In addition, the application of machine learning and spatial analysis is now enriching the use of VCR data in transportation policies. [48] show that artificial intelligence-based VCR data processing can predict congestion patterns and help design adaptive policies in real-time. [49] added that VCR analysis integrated with travel speed data provides more comprehensive evaluation results of urban transportation system efficiency. Meanwhile, the average travel speed describes the efficiency of vehicle movement on a road section under certain conditions. A decrease in travel speed is often the first signal of increased congestion levels and reduced performance of the transportation system. [50] show that travel speed analysis can serve as a dynamic indicator in evaluating vehicle restriction policies and traffic engineering in large cities. Mileage data is collected through field surveys, traffic sensor systems, or GPS-based technologies integrated in traffic monitoring applications. [51] affirm that the use of GPS data and big data analytics allows real-time evaluation of transportation policies, improving the government's ability to adapt policies to actual traffic conditions. Another study [52], [53] highlights that combining travel speed data with travel demand models helps governments map peak times of congestion and assess the effectiveness of policies such as odd-even systems. Velocity-based evaluations and VCRs enable more targeted decision-making, based on real evidence in the field. This approach is in line with the principles of evidence-based policy making which emphasizes the importance of using empirical data in the public policy cycle. [54] showed that the integration of travel speed data and VCR in digital transportation monitoring systems can improve the efficiency of traffic policies compared to conventional approaches. Thus, the use of data-driven indicators such as VCRs and travel speed is not only a technical evaluation tool, but also a strategic means in ensuring that transportation policies are more responsive, efficient, and sustainable. The application of data-based policy evaluations such as VCR and travel speed is highly relevant to the concept of evidence-based policy making (EBPM), where every public policy is based on empirical data and scientific analysis, rather than just assumptions or political pressure. This approach strengthens government transparency and accountability, as each policy can be tested for effectiveness through measurable indicators sourced from field data. [55] explain that EBPM helps governments assess policies rationally and reduce subjective bias in the policy formulation process. In other words, transportation policies based on objective data are better able to produce real impacts in improving mobility efficiency and road safety.

In practice, EBPM in the transportation sector is used to assess the effectiveness of interventions such as vehicle restriction policies, traffic light timing, and the development of alternative infrastructure. After the traffic management policy is implemented, the government can conduct periodic evaluations by comparing the value of the VCR and the travel speed before and after the implementation. [56] emphasized the importance of the feedback policy loop mechanism, where the results of quantitative evaluation are the basis for subsequent policy improvements. Another study [57] shows that the implementation of EBPM improves the consistency and sustainability of transportation policies because policies are based on publicly verifiable evidence. Data-driven evaluation also requires an integrated information collection and processing system. The government needs to build a National Transport Information System that can collect data from various sources—both from government agencies, transportation operators, and the private sector. [58]

emphasizes the importance of big data analytics-based transportation information systems to understand the dynamics of urban mobility and design policies that are adaptive to changes in time and space. With the support of technologies such as the Internet of Things (IoT) and artificial intelligence (AI), the evaluation process is no longer static, but can be done in real-time. [59] showed that the integration of traffic data through IoT can increase decision-making speed by up to 35% compared to conventional methods.

In addition to the technological aspect, the effectiveness of EBPM also depends on the quality of data and coordination mechanisms between institutions. [60] highlight that collaboration between agencies, such as the ministry of transport and research institutes, is important to avoid duplication of data and ensure consistency of evaluation indicators. In the context of transport policies in developing countries, cross-sectoral coordination is a major challenge, as differences in administrative systems and technical capacity between regions can slow down the integration of transport information systems [31]. In addition, the participation of the public and academics in the policy evaluation process strengthens the legitimacy of the evaluation results. [61] stated that the involvement of external stakeholders, such as universities and research institutions, can increase the credibility of the EBPM process because it adds an independent perspective to the analyzed data. By involving the public and experts, the government gains a broader view of the social, economic, and environmental impacts of the transportation policies implemented. The use of open data is also an important component in supporting transparent EBPM. [62] affirm that the integration of open data in policy evaluation systems increases public participation and advises innovation in public policy analysis from Guangdong-Hong Kong-Macao Greater Bay Area. Furthermore, [63], [64] added that big data-based policies accompanied by strong data governance can accelerate digital transformation in the public sector and strengthen long-term policy effectiveness. Thus, the application of EBPM in transportation policy evaluation not only serves to assess the effectiveness of the policies that have been implemented, but also to strengthen data-driven governance. Through the integration of technology, institutional coordination, and public participation, data-driven evaluations can be a strong foundation for the formation of a responsive, efficient, and sustainable transportation system in the digital age.

Data-driven evaluations not only serve to assess policy success, but also serve as a key basis for future transportation policy planning. The results of the analysis of the VCR and travel speed can help the government determine the priorities of infrastructure development more strategically. [65] show that the longitudinal use of traffic performance data allows transportation planners to identify areas with urgent needs for infrastructure capacity building. The data shows not only where congestion occurs, but also how certain policy changes affect overall mobility, both in urban and interregional areas. Furthermore, the integration of travel speed data in transportation planning systems provides an empirical basis for determining the location of public facility construction and adaptive working hours setting. [66] found that real-time data-based travel speed analysis plays an important role in supporting dynamic traffic management policies that are able to reduce travel time by up to 20% in dense urban areas. This approach is also used to support zoning-based transportation policies, which link mobility data with land use to improve the balance between demand and capacity of transportation networks. Thus, the evaluation process becomes an integral part of the public policy cycle—from formulation, implementation, to the continuous improvement stage. [56] emphasize the importance of integrating empirical evaluation into every stage of transportation policy so that every decision can be reviewed based on real results on the ground. Evaluation is no longer considered as the final stage, but rather as a policy feedback loop mechanism that strengthens the effectiveness of public policies.

The implementation of data-based policy evaluations such as VCR and travel speed also advises improvement in the quality of national transportation governance. [67] asserts that evidence-based public policy strengthens the credibility of government institutions and creates a culture of rational and efficient decision-making. In addition, [68] highlight that the implementation of an open data-based evaluation system strengthens public transparency and allows the public to participate in monitoring policy achievements independently. This is important in the context of governance that is oriented toward accountability and community participation. On the other hand, the application of data-based evaluation also contributes significantly to the efficiency of the use of public resources. [55] stated that transportation policies based on data analysis have a greater economic impact because they are able to minimize investment risks and optimize budget use. The same thing was conveyed [69], [70] who explained that the integration of big data analytics in urban policy evaluation can direct infrastructure investment in areas with the highest socio-economic benefits. Furthermore, good transportation data management also plays a role in creating a fair and inclusive mobility system. [71], [72] assert that the data-driven governance approach allows public policies to be more responsive to vulnerable community groups, such as public transportation users and pedestrians. With this approach, policy evaluation assesses not only technical efficiency, but also social impact and equitable access to transportation services. Finally, the successful implementation of data-driven evaluation requires an institutional framework that supports inter-agency and cross-sectoral collaboration. [73] highlight the importance of building a standardized national data architecture to ensure inter-regional consistency in transportation data collection and analysis. Through an integrated data system and the active participation of all stakeholders, Indonesia can realize more efficient, transparent, and sustainable transportation governance for all levels of society.

6.4. Synergy between Public Policy and Transportation Engineering

The synergy between public policy and transportation engineering is the main foundation in creating an effective, efficient, and sustainable mobility system. Public policy serves as a normative framework that determines the direction of transportation development, while transportation engineering provides a scientific and methodological basis for designing and evaluating the implementation of such policies. According to [56], without integration between policy approaches and technical analysis, transportation systems often fail to address real challenges on the ground because strategic decisions are not based on scientific evidence. Therefore, collaboration between sectors is an urgent need to ensure that any transport policy has a strong technical basis and measurable impact. In practice, this synergy starts from the planning stage. Effective public policies must be built on the results of in-depth technical studies, such as mobility needs analysis, vehicle growth projections, and road network capacity evaluations. [74], [75] emphasized that the integration of transport demand forecasting results and network assignment modeling into public policy processes helps ensure more efficient resource allocation. This data-driven approach and transportation model also strengthens policy credibility by providing a scientific basis that can be tested and replicated. Transportation engineering also provides analytical tools that help policymakers assess the socio-economic benefits of infrastructure projects. [76], [77] show that the use of cost-benefit analysis (CBA) in transportation planning can minimize the risk of wasting public budgets and ensure that investments provide maximum benefits to accessibility and economic productivity. Meanwhile, [78] highlight that a combination of CBA and multi-criteria analysis is important for incorporating social and environmental aspects into transportation policy decision-making. In addition, advances in spatial analysis technology and big data have also strengthened the synergy between transportation engineering and public policy. showed that the application of urban data analytics allows the government to monitor real-time changes in movement patterns and dynamically adjust transportation policies. On the other hand, [79] affirm that the use of GIS and traffic prediction models supports evidence-based transport policymaking, which strengthens the effectiveness of implementation in the field. The synergy between public policy and transportation engineering also includes institutional and governance aspects. [80] explain that data-driven governance advises cross-sector collaboration between technical planners, policymakers, and academics in formulating inclusive transportation solutions. Meanwhile, [81] added that the success of science-based policies is highly dependent on the ability of government agencies to translate the results of transportation engineering research into strategic decisions that can be implemented. Furthermore, [82] show that the use of ITS as a result of transportation engineering innovations can accelerate the adaptation of traffic policies to real-time conditions, for example in adaptive signal management or congestion control. The implementation of ITS combined with adaptive transportation policies has been proven to improve travel efficiency and reduce carbon emissions in the world's major cities. Thus, the synergy between public policy and transportation engineering is not only a matter of administrative coordination, but also a paradigm unification between engineering and public governance. This approach allows for policy formulation that is not only responsive to technical and environmental challenges, but also inclusive of the social needs of the community. As emphasized [83], transportation policies based on cross-disciplinary collaboration are the main keys to realizing an efficient, fair, and sustainable mobility system.

In addition, the implementation of public policies based on transportation techniques can significantly increase the effectiveness of solutions to traffic and urban mobility problems. Technical approaches such as the design of traffic signal coordination, one-way traffic systems, and the construction of grade separation (flyovers and underpasses) not only serve as physical engineering solutions, but also as an integral part of public policies designed to optimize vehicle flow and reduce travel time. [84] [85] show that the integration between traffic control policies and road design techniques can increase the capacity of the transportation network in areas with high vehicle volumes. This approach emphasizes the importance of collaboration between policy institutions and transportation experts in formulating data-based and behavior-based strategies for road users. In the context of congestion control policies, the implementation of traffic engineering measures has proven to be more effective when accompanied by regulations based on law enforcement and traffic demand management. [86] explained that the synergy between regulation-based policies and engineering approaches, such as one-way systems and adaptive signal arrangements, can reduce congestion levels in large metropolitan areas. Thus, public policy not only regulates the flow of vehicles administratively, but also results in real changes to the efficiency of the traffic system. Furthermore, advances in modern transportation technology have opened up great opportunities for integration between public policy and transportation engineering innovation. Governments can now leverage ITS to support data-driven decision-making quickly and accurately. [87] showed that the implementation of ITS that combines traffic sensor data, CCTV cameras, and vehicle GPS can improve the efficiency of traffic regulation, while reducing peak congestion times. The use of smart technology in public policy also allows for real-time analysis to detect congestion, dynamically regulate traffic light signal timing, and provide direct information to road users. [79] affirm that the use of GPS data and artificial intelligence-based traffic prediction models strengthens the government's ability to respond to changes in daily mobility patterns. With public policies that are adaptive to this data, transportation planning can be carried out more precisely and sustainably. In addition to improving operational efficiency, the integration of intelligent technology also contributes to the safety and sustainability of transportation systems. [88] show that transportation policies that combine ITS with data-driven supervision can reduce the rate of traffic accidents and save vehicle fuel consumption. Meanwhile, [89] highlights the role of urban data analytics in helping urban planners optimize the use of street space and integrate public transportation modes through interconnected information systems. The implementation of ITS-based policies also strengthens the principle of evidence-based governance, where transportation decisions are made based on empirical evidence and continuous monitoring. [81] explain that data-driven decision-making not only improves government transparency and accountability, but also drives public trust in transportation policy. This is reinforced by the findings of [90] who stated that data-based transportation policies and digital innovations can accelerate the transformation toward a more inclusive and environmentally friendly mobility system. Thus, the synergy between public policy and modern transportation techniques creates a smart mobility ecosystem. Through policies that encourage the use of technology such as ITS, big data, and AI, the government is not only able to improve traffic efficiency, but also strengthen aspects of safety, energy efficiency, and user comfort. As stated by [91], the implementation of data-based public policies and digital technologies is a fundamental step toward sustainable transportation governance that is responsive to future challenges.

Synergy between public policy and transportation techniques is also needed in the development of sustainable transportation systems that are adaptive to social, economic, and environmental changes. Technical aspects such as public transportation route planning, bicycle lane design, and pedestrian area arrangement must be designed in an integrated manner with green and low-emission mobility policies. This approach is in line with the sustainable urban mobility planning (SUMP) paradigm, where public policies are directed to reduce dependence on private motor vehicles and encourage the use of low-carbon modes of transportation. [92] assert that the integration between technical transportation planning and sustainability-based public policy can reduce the carbon emissions of the transportation sector by up to 25% in metropolitan areas. The TOD area development policy is a concrete example of this synergy. TOD combines spatial planning principles, transportation techniques, and public policy to create an integrated area between residence, work, and public transportation. [93] state that the success of TOD depends on synchronization between technical planning of transportation networks and consistent regulatory support, especially related to zoning and investment incentives.

Without strong policy support, good technical design often cannot be implemented optimally. Collaboration between urban planners, transportation engineers, and public policymakers is a key factor in ensuring a balance between economic development, transportation efficiency, and environmental sustainability. [94] highlight the importance of integrated planning frameworks that combine technical analysis, spatial policy, and economic policy to achieve mobility efficiency and equitable transportation access. This cross-disciplinary approach helps avoid policy conflicts between agencies and accelerates the implementation of environmentally friendly infrastructure projects. From an institutional perspective, the synergy of transportation policies and techniques requires strong cross-sectoral coordination between various government agencies. [95] show that one of the main causes of transportation policy failure is institutional fragmentation and weak communication between public organizations. Therefore, a transportation governance mechanism is needed that ensures alignment between national policies and technical implementation in the regions. The Ministry of Transportation, the Ministry of PUPR, local governments, and regional planning agencies must operate within one integrated policy framework. [96] stated that strengthening coordination between institutions and a clear division of roles can accelerate the implementation of sustainable transportation up to twice as fast as sectoral systems. The national transportation coordination forum or regional transportation council can function as a strategic forum to unite visions, bring together interests between parties, and align policies with technical conditions in the field. In addition, the integration of public policy and transportation techniques must also pay attention to social aspects and community participation. [97] show that transportation policies that involve the community in the technical planning stage have a higher level of public acceptance and reduce social conflicts against infrastructure development. This participation not only creates policy legitimacy, but also enriches the technical design process with contextual, local insights. From a technological perspective, the integration of sustainable transportation systems also requires the support of digitalization. [98] highlight that the implementation of smart urban mobility frameworks supported by digital technology, data analytics, and the IoT can strengthen the effectiveness of public transportation policies and improve coordination between government agencies. With this technology, transportation data from various sectors can be integrated to support responsive and evidence-based policies. The success of synergy between public policy and transportation engineering depends on governance quality and institutional capacity. [99] emphasize that institutional reform and coordination mechanisms between levels of government are the main foundations for realizing an inclusive and efficient national transportation policy. Therefore, sustainable transportation development depends not only on technological advances and engineering design, but also on the ability of governments to manage collaboration between sectors, ensure policy transparency, and maintain consistency in development directions.

In addition to institutional coordination, human resource capacity also plays an important role in realizing synergy between public policy and transportation engineering. Policymakers need to have a basic understanding of the principles of transportation engineering, while transportation engineers need to understand the social, economic, and political context of the public policies they support. According to [100], cross-disciplinary skills between technical planners and policymakers are a key factor in producing urban mobility systems that are adaptive to the needs of communities. Such collaboration can be facilitated through formal education, professional training, and academic forums that bring the two fields together on an ongoing basis. Strengthening the capacity of human resources also requires updating the higher education curriculum in the field of transportation and public policy. [101] highlight the importance of an interdisciplinary approach in transportation planning education to build a comprehensive understanding between technical and social aspects. In this context, universities and research institutions have a strategic role as a bridge between scientific knowledge and public policy practice. Through the integration of education and policy research, decision-makers can utilize the results of empirical studies in EBPM. Thus, the resulting transportation policy can answer the needs of the community in a more precise, fair, and sustainable manner. [102] show that public policies built on the basis of technical analysis and community participation are able to increase policy effectiveness by up to 30% compared to traditional top-down approaches. This approach reinforces social justice in transportation policy, while ensuring that technical decisions take into account the interests of all groups of people. The synergy between public policy and transportation engineering not only results in good physical infrastructure, but also creates an efficient and humane mobility system. [103] emphasized that transportation policy design that pays attention to the technical aspects of traffic engineering and road user behavior can improve the quality of public transportation services and reduce the burden on national logistics. On the other hand, the application of transportation engineering principles in line with public policy ensures that any infrastructure development supports the long-term vision of national development. According to [104], strengthening synergy between public policy and transportation engineering can accelerate the achievement of the Sustainable Development Goals (SDGs), especially in the fields of mobility, energy, and climate change mitigation. This is because this synergy allows for the creation of holistic policies, taking into account social, economic, and environmental impacts in a balanced manner. In the Indonesian context, the biggest challenge in building this synergy is to strengthen inter-agency collaboration and create a policy-oriented technical training system. [99] argue that developing countries need institutional reforms that allow for ongoing dialogue between policy makers and engineering experts so transport policies to be implemented effectively. Furthermore, [105] emphasize that partnerships between the public sector, academia, and the transportation industry can result in policy innovations that are more resilient to technological changes and the global climate. By strengthening the dialogue between stakeholders, transportation policies can continue to be adapted to technological developments such as electric vehicles, autonomous transportation systems, and the digitization of mobility data. Finally, according to [106], the success of the synergy of public policy and transportation engineering is determined by the extent to which these two disciplines can share data, resources, and shared development visions.

Table 6.1. Public Policy in Infrastructure Management

Components	Brief Description
1. General Purpose (Goal)	Realizing an efficient, sustainable, inclusive national infrastructure and transportation system that supports economic growth and equitable development between regions.
2. Special Purpose	- Improving the effectiveness of public policies in the management and development of national road infrastructure.- Reducing congestion levels and improving the efficiency of urban mobility.- Building a transparent and accountable data-based policy evaluation mechanism.- Realizing synergy between public policy and transportation techniques.
3. Input	- National regulatory and policy framework (Law Number 38/2004, RPJMN, RUJRN).- Technical data on transportation (VCR, travel speed, road conditions).- Human resource support (government, academics, transportation planners, private sector).- Transportation technology and information systems (ITS, big data, IoT).- Financing schemes (State Budget, PPP, private investment).
4. Process / Activities	Part 1: Formulation of policies for the development of the national road network based on efficiency and sustainability. Part 2: Implementation of public policies to address congestion through the development of mass transportation, traffic management, and ITS. Part 3: Policy evaluation using VCR and travel speed indicators, based on real-time data and *EBPM*. Section 4: Strengthening synergy between public policy and transportation engineering through cross-agency coordination, HR training, and the application of smart technologies.
5. Output (Direct Output)	- The preparation of a targeted and data-based national road policy.- Reduced vehicle volume and increased traffic efficiency in big cities.- The availability of a transportation policy evaluation system based on quantitative indicators.- Coordination between policymakers and transportation engineering experts.
6. Outcome	- Increasing the effectiveness of national transportation infrastructure management.- Realization of an efficient and sustainable urban mobility system.- Developing transparent, participatory, and data-based transportation policy governance.- Strengthening the capacity of human resources and national transportation institutions.
7. Impact	- Increasing national economic competitiveness through logistics efficiency and mobility.- Equitable distribution of development between regions through national road connectivity.- Realization of national transportation that is environmentally friendly, inclusive, and future-oriented.

Source: Author analysis, 2025

Consistent collaboration between planners, engineers, and policymakers enables the creation of transportation systems that are adaptive to rapid urbanization, vehicle growth, and the demands of green mobility. By strengthening this synergy, Indonesia can build resilient, inclusive, and highly competitive national transportation in the modern era. Public policy in infrastructure management plays a strategic role in realizing national connectivity, equitable development, and efficiency of community mobility (Table 6.1.). Through targeted planning and policy implementation, the government seeks to develop a national road network that not only serves as a means of transportation, but also as a key driver of economic growth and regional integration. The implementation of public policies in overcoming congestion reflects the government's commitment to provide innovative solutions, both through the development of mass transportation and the application of smart technology in traffic management. Data-driven policy evaluations such as the use of VCR and travel speed strengthen the basis for more objective and measurable government decision-making. This EBPM approach ensures that every policy taken can be measured for its effectiveness and adjusted to the dynamics of conditions in the field. Meanwhile, the synergy between public policy and transportation engineering is an important foundation in creating an efficient, safe, and sustainable transportation system. The integration between regulatory, technical, and social aspects allow every infrastructure policy to run in harmony with the needs of society and the development of modern technology. The success of infrastructure management depends not only on good policies, but also on the ability of the government and all stakeholders to work collaboratively. Synergy between policies, data, and technology is the key to a resilient, adaptive, and highly competitive national transportation system. With a sustainable and evidence-based policy direction, Indonesia can continue to strengthen its infrastructure foundation as a driving force for inclusive and equitable national development for all people.

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CHAPTER 7
ROAD AND BRIDGE ENGINEERING

Ari Sasmoko Adi | Andjar Prasetyo

The development of transportation infrastructure is one of the main pillars in supporting economic growth, population mobility, and the distribution of goods in a region. Roads and bridges as vital elements of the land transportation system play a role in connecting the centers of economic, social, and cultural activities. Therefore, road and bridge engineering is not only concerned with the technical aspects of construction, but also includes planning, design, maintenance, as well as environmental sustainability. In the context of national development, the ability to design and build reliable, safe, and environmentally friendly infrastructure is an indicator of the progress of civil engineering civilization in a country. This chapter discusses the basic principles in road and bridge engineering as a foundation for understanding the design and implementation of land transportation projects. The discussion started from the conceptual aspect, including the relationship between road functions, classification, and geometric characteristics that are adjusted to topographic conditions and traffic needs. Furthermore, it will be discussed how road design must consider natural factors such as land slope, soil type, water system, and potential impact on the environment. The integration between technical design and ecological conditions is an important factor to ensure efficient and sustainable road construction.

In addition, this chapter presents a case study on the repair of the Kapuas 1 Twin Bridge in Pontianak, which is a concrete example of the application of structural engineering, project management, and sustainability principles in the context of strategic infrastructure in Indonesia. Through this study, readers are expected to understand the challenges and solutions in the rehabilitation of existing bridges that maintain the function of transportation without interfering with community activities. In closing, the discussion was directed to the importance of integration between road engineering and environmental engineering, which is a modern approach in green infrastructure development. This approach emphasizes the importance of balancing technical efficiency and ecosystem sustainability through the application of the concept of sustainable roads (green roads), environmentally friendly drainage systems, and social impact management. Thus, Chapter 7 is expected to provide a comprehensive understanding of how modern civil engineering principles are applied in designing and managing resilient, efficient, and environmentally sound transportation infrastructure.

7.1. Basic Principles of Road and Bridge Engineering

Road and bridge engineering is one of the main fields in civil engineering that focuses on the planning, design, construction, and maintenance of land transportation infrastructure. Its main goal is to create a safe, efficient, economical, and sustainable transportation system to support human mobility and the distribution of goods. The basic principles in road and bridge engineering include structural, functional, and environmental aspects that are intertwined to produce reliable and durable infrastructure. In the context of road engineering, the main principle that must be considered is the suitability between the function of the road and its classification. Arterial, collector, local, and environmental roads have different geometric characteristics, capacities, and technical standards according to their role in the transportation network. Road geometric design includes the arrangement of elements such as horizontal and vertical alignments, flatness, lane width, road shoulders, and curve radii that are adjusted to the planned speed and local topographic conditions. This principle aims to ensure comfort, safety, and energy efficiency during vehicle operation. According to research [1], geometric designs that do not match the characteristics of vehicles can increase the risk of accidents by up to 25% in high-elevation areas. In addition, performance-based design-based approaches are beginning to be applied in road engineering to assess the structural behavior of pavement based on dynamic load conditions and local climate [2].

In the context of pavement, the selection of materials is an important aspect to ensure resistance to traffic loads and extreme weather conditions. A study [3] showed that the application of reclaimed asphalt pavement (RAP) with polymer additives was able to increase the service life of the road by up to 30% without increasing construction costs. This is in line with the sustainability approach emphasized [4], who highlight the importance of life-cycle assessment in determining pavement material efficiency and reducing carbon emissions during construction. In safety, road design must pay attention to driver visibility, surface drainage systems, and road equipment such as signs, markings, and lighting. According to [5], increased visibility and street lighting significantly lower the number of nighttime accidents on urban arterial roads. On the other hand, suboptimal surface water management can accelerate pavement degradation as well as reduce the level of safety due to aquaplaning. [6] emphasize the importance of adaptive drainage design for tropical regions that are prone to high rainfall. For bridge structures, engineering principles emphasize strength, rigidity, and stability against traffic loads and environmental loads. According to [7], the use of a prestressed concrete girder system with real-time monitoring sensors increases structural resilience and facilitates early detection of damage. Another study [8] highlighted the benefits of modular design in bridge maintenance, which allows for time and cost efficiencies during rehabilitation. From an environmental perspective, the incorporation of road and bridge engineering principles with an ecotechnical approach is important to ensure sustainability. [9] emphasized the importance of using geopolymer-based green pavement materials to reduce global carbon impact in the transportation sector. The integration between structural design, energy efficiency, and environmental conservation reflects a new direction in road and bridge engineering that is oriented toward infrastructure resilience as well as long-term sustainability.

In road structure engineering, material strength and pavement thickness are fundamental aspects to ensure resistance to traffic loads and environmental conditions. Based on the results of a review of eight recent international publications, various approaches have been developed to analyze the performance of bending and rigid pavement, including traffic load modeling with Equivalent Single Axle Load (ESAL) units as well as the application of new analytical technologies for the prediction of pavement deformation. A study [10] developed a machine learning framework to predict the roughness of bending pavement under various climatic conditions, showing that the Extreme Gradient Boosting model provides the highest accuracy in predicting the International Roughness Index. Another study [11] showed that the use of geogrids in portland cement concrete joints can reduce vertical deformation by up to 75% and strain on asphalt layers by up to 92.5%, signaling a significant improvement in compound pavement performance. Analysis of the decrease in modulus of elasticity is also an important focus. [12] and [13] developed a deterministic International Roughness Index (IRI) model for flexible, semi-rigid, and composite pavement, with bitumen layer thickness as a key variable affecting long-term performance. In addition, [14] used machine learning to predict the development of rutting on asphalt pavement, with the Gradient Boosting Decision Tree model providing the best results ($R^2 = 0.9833$). [15] also emphasized the importance of evaluating the age of the remaining pavement with the Falling Weight Deflectometer method to plan road rehabilitation due to increased traffic load.

From the perspective of modern structural engineering, the concept of road and bridge design now emphasizes the integration between material efficiency, structural resilience, and environmental sustainability. The use of geopolymer concrete is gaining attention because it has low carbon emissions, high strength, and long-term durability, making it suitable for application to bridge elements such as beams and main slabs [16]. In addition, polymer-based concrete exhibits a better strength-to-weight ratio, high chemical resistance, and supports circular economy principles through the use of recycled materials [17]. Ultra-high-performance concrete (UHPC) technology is also an important innovation in long-span bridges because it can provide exceptional compressive strength and durability despite the high cost of production [18]. In the context of construction efficiency, precast and segmental bridge construction methods continue to be developed to accelerate implementation and improve quality control. The modular construction trend is also increasingly relevant in efforts to reduce construction waste and energy consumption [19]. The application of earthquake-resistant designs on bridges is a major concern in disaster-prone areas. A study in the Proceedings of the Italian Concrete Conference 2022 emphasizes the importance of rehabilitation and seismic upgrading using innovative materials and high-performance concrete [20]. In line with that, life-cycle management principles are applied to extend the life of infrastructure services through periodic inspections and predictive maintenance. The direction toward net-zero infrastructure is also underlined in Innovations for Sustainable and Resilient Infrastructure which highlights innovative materials, construction automation, and sustainable management policies to minimize carbon emissions [21]. The support of digital technologies such as digital twins and smart monitoring in structural supervision also strengthens the concept of sustainability, as mentioned in the Proceedings of the 8th International Conference on Civil Engineering [22]. Today's road and bridge engineering is transforming into a discipline that combines structural strength, time efficiency, and environmental responsibility—creating resilient, efficient, and sustainable infrastructure.

7.2. Road Design Based on Topography and Environment

Good road design is determined not only by traffic needs, but also by its suitability to topographic conditions and the surrounding environment. Each location has unique physical and ecological characteristics, so the road design must adjust to the shape of the land, soil conditions, land use, and social and economic factors of the surrounding community. The main goal of this approach is to produce a design that is functional, safe, economical, and minimizes negative impacts on the environment and local ecosystems.

7.2.1. The Influence of Topography on Road Design

Topography is a fundamental element in road geometric planning because it affects the shape, slope, and stability of the trase. In flat areas, the road design is relatively simple due to the high stability of the slope. However, in hilly or mountainous areas, the maximum slope factor, bend radius, and slope stability are the main determinants in planning. Recent studies show that dynamic algorithm-based track optimization approaches and Bayesian modeling can be used to balance construction costs, landslide risk, and environmental impacts in road and rail design [23]. In the context of slope stability and drainage, recent geotechnical research highlights the importance of groundwater flow modeling on fractured rock masses to prevent collapse due to seepage [24]. This principle is the basis for the design of roadside drainage systems and culverts in sloping areas to reduce the risk of erosion and pavement damage. In addition, the use of geosynthetics has been shown to be effective in increasing slope stability and strengthening the backfill layer on steep terrain. This material helps maintain a balance between excavation and heap and reduces subsoil deformation [25]. This approach is in line with the principles of resilient earthwork design which focuses on material use efficiency and long-term durability. Runoff control in mountainous areas is also a concern in modern hydraulic studies that emphasize the importance of integrated drainage systems to prevent erosion and collapse of road shoulders [26]. In the context of planning a cross-river road, the use of tunnel systems or underground bridges has been studied as an efficient solution to extreme topographic conditions, taking into account safety factors and construction costs. Furthermore, research on life-cycle design on land infrastructure shows that geometric design of roads that considers long-term risk factors and preventive maintenance results in higher cost efficiencies [27]. This approach is in line with efforts to build resilient and sustainable transportation systems through the application of green engineering and the use of environmentally friendly materials in earthworks and drainage [28]. Thus, the geometric design of roads in hilly areas demands a balance between safety, economic efficiency, and sustainability. The integration of trase optimization technology, slope stabilization with geosynthetics, and drainage systems that are adaptive to extreme topography are key to producing reliable and safe infrastructure.

7.2.2. Geotechnical and Soil Structure Considerations

Subgrade soil structures play a crucial role in ensuring the stability and service life of the road, especially due to the significant variation in soil conditions in various regions. In swamp or alluvial valley areas with soft soils and low carrying capacity, soil improvement methods such as soil stabilization, preloading, and the use of geosynthetics are important steps. Global bibliometric studies confirm that the topic of special soil reinforcement has become a major focus of international geotechnical research with strong trends in geosynthetic technologies and advanced materials [29]. The application of geosynthetics such as geogrid, geotextile, and geomembrane has proven to be effective in increasing soil carrying capacity and reducing differential deformation. Experimental and numerical research show a significant increase in soil bearing capacity as well as control of foundation subsidence when geosynthetic layers are optimally applied [30]. Another study highlights that geosynthetics double as a mechanical reinforcer as well as an erosion controller, allowing for the design of more efficient and environmentally friendly soil structures [31]. In the context of soft soil soils, recent research in Ground Improvement II, Proceedings of the Indian Geotechnical Conference 2023 emphasizes the importance of combining analytical approaches and numerical modeling to optimize soil improvement techniques [32]. Meanwhile, geofoam and geocell technologies are now widely used to reduce differential deformation and improve the stability of heaps in soils with high compressibility properties, as presented in Geosynthetics: Leading the Way to a Resilient Planet [25]. In rocky and hilly areas, cutting work requires a careful geotechnical approach, including slope stability analysis and the application of reinforcement systems such as retaining walls designed with safety factors in mind. In the Proceedings of the Indian Geotechnical Conference [33], the volume related to Soil-Structure Interaction and Transportation Geotechnics discusses modern engineering strategies in stabilizing slopes through a combination of numerical techniques and field tests. The application of geotextiles and geogrids in soil reinforcement also contributes to resistance to erosion, increases drainage capacity, and extends the life of ground land infrastructure. A recent study in Discover Civil Engineering emphasizes that geosynthetics is now an eco-friendly solution for soil reinforcement that can replace conventional materials efficiently and sustainably [34]. Modern basic soil engineering requires the integration of soil mechanics, materials engineering, and digital technologies approaches to produce stable, cost-effective, and sustainable designs.

7.2.3. Environmental Aspects in Road Design

Road construction has a wide potential for environmental impacts, including changes in water systems, habitat degradation, to increased noise and air pollution. Therefore, the implementation of an Environmental Impact Assessment (EIA) is an important first step in the design process to identify and mitigate ecological and social risks. Global studies show that road construction in sensitive regions, such as the mountainous regions of Asia and the Arctic, often gives rise to long-term ecological footprints in the form of hydrological and habitat disturbances, especially due to the lack of a thorough environmental impact evaluation [35]. In the context of adaptive planning, the elevated road approach or small bridges is used to maintain the continuity of water flow and animal migration routes. Research in Bangladesh confirms the importance of GIS-based impact assessment methods and Leopold matrix in detecting the risk of water system change and loss of productive land due to bridge projects [36]. Meanwhile, a study in Sweden shows that forest road infrastructure has a dual effect, in addition to facilitating economic access, it also has the potential to disrupt hydrology and wildlife ecosystems, thus demanding adaptive multi-functional planning [37]. The drainage aspect is key in minimizing the impact of runoff and erosion. A study in Geographic Approaches to Climate Change and Mitigation emphasizes the importance of implementing nature-based solutions such as slope vegetation, retention ponds, and planned infiltration systems to maintain natural hydrological balance [38]. A similar approach is also being implemented in New York State through low-emission transportation infrastructure policies that consider environmental justice and resilience to climate change [39]. In addition to the physical environment, road design needs to pay attention to social and aesthetic aspects. A study in Lagos, Nigeria, shows that without noise mitigation and good spatial planning, road improvement projects can worsen the quality of life of citizens [40]. The sustainable urban approach now includes noise barrier elements, green vegetation, as well as bicycle and pedestrian paths to improve public comfort and support green mobility. Modern road planning is no longer just about meeting transportation needs, but also an instrument for achieving ecological and social balance. The integration of EIAs, adaptive design of ecosystems, and the implementation of nature-based solutions are key to realizing a resilient and sustainable transportation infrastructure.

7.2.4. Integration of Topographic and Environmental in Design Sustainability

Modern design approaches in road engineering demand integration between topography, environment, and sustainability. The concept of context-sensitive design (CSD) ensures that infrastructure design is in harmony with natural conditions and the social needs of the local community. Recent studies show that the integration of digital technologies such as Building Information Modeling (BIM) and Geographic Information Systems (GIS) has revolutionized the way designers understand the interaction between geotechnical, hydrology, and the environment in transportation projects [41]. The Civil Integrated Management (CIM) approach expands the use of digital data across project stages through 3D geospatial models and digital twins for the sustainable planning, maintenance, and rehabilitation of transportation infrastructure [42]. In the context of sustainability, the application of Industry 4.0 technologies such as IoT, sensors, and artificial intelligence (AI) is increasingly playing a role in improving energy efficiency and monitoring environmental conditions during the road life cycle [43]. BIM–GIS integration also plays an important role in disaster risk mitigation and adaptive planning, especially in coastal and mountainous areas that are vulnerable to abrasion, landslides, and floods. This integrated system enables real-time spatial visualization and risk-based planning, as demonstrated in a study on urban disaster management [44]. In addition, the application of AI and machine learning technology has been proven to improve the accuracy of predicting slope stability, pavement conditions, and rainwater flow patterns which are important aspects in road topography planning [45]. Furthermore, the integration of geotechnical and environmental data in digital models allows for more adaptive design to local conditions, such as swampy soils or steep slopes. This approach strengthens the application of sustainability principles through material efficiency, construction emission reduction, and water resource conservation [46]. Virtual Reality-based (VR)-based technologies are now also being utilized in geomatics engineering to simulate road design and its impact on landscapes and ecosystems, aiding in more transparent and participatory decision-making [47]. Modern road design that combines CSD, GIS, and BIM results in infrastructure that is not only technically resilient but also harmonious with the environment and society. This data-driven approach accelerates the transformation toward sustainable transportation that is adaptive to natural and social dynamics.

7.3. Repair of Kapuas Bridge 1 Twin Bridge in Pontianak

The Kapuas 1 Bridge in Pontianak is one of the important infrastructures that functions as the main link between two areas on the banks of the Kapuas River, namely Pontianak City and East Pontianak. With a main span length of about 400 meters, this bridge is a vital route for intercity traffic flow and logistics distribution in West Kalimantan. As the city grew and the traffic load increased, the bridge experienced a decline in structural performance, which then prompted the government to carry out a repair and strengthening project, known as the Kapuas 1 Twin Bridge project. This case study provides an overview of how the principles of structural engineering, project management, and sustainability are applied in an integrated manner in the repair of large bridges in the tropics. The Kapuas 1 Bridge was built in the early 1980s and has served more than four decades of operation. Over time, the increased volume of heavy vehicles, environmental influences such as high humidity, as well as corrosion exposure due to sea and river air lead to material degradation, especially in steel elements and joints. The results of structural inspections showed a decrease in load capacity, cracks in concrete elements, and a decrease in the quality of the steel protective layer. Therefore, a technical study was carried out to determine an efficient rehabilitation method without significantly disrupting the flow of heavy traffic. In addition to technical factors, the urgency of repair is also influenced by the increasing need for urban mobility in Pontianak. Rapid economic growth creates congestion around the bridge area, so more capacity or twin bridges are needed to divide the traffic flow. The concept of these twin bridges is not only aimed at increasing capacity, but also as an effort to redundancy the structure, so that if one bridge needs maintenance, the traffic flow can still function through the other bridges.

The Kapuas 1 Bridge in Pontianak is a strategic infrastructure that is now the focus of improvement through the Kapuas 1 Twin Bridge project to increase the capacity and resilience of the structure. The principle of life-cycle management is the foundation of this rehabilitation strategy, where structural condition evaluation, preventive maintenance, and material replacement planning are carried out systematically to extend the service life of the bridge [48]. The latest study confirms that the life-cycle engineering-based approach can optimize maintenance costs while reducing the risk of structural failure due to material degradation on bridges in humid and corrosive environments such as in West Kalimantan [49]. In tropical contexts, the combination of increased traffic loads, high humidity, and chloride exposure leads to accelerated corrosion in steel elements and cracks in concrete, so reinforcement strategies should include anti-corrosion coatings and the use of high-performance composite materials [50]. Annual research on bridge engineering advances shows that sensor-based intelligent monitoring systems and digital technology are becoming important solutions in detecting structural degradation early as well as improving maintenance efficiency [51].

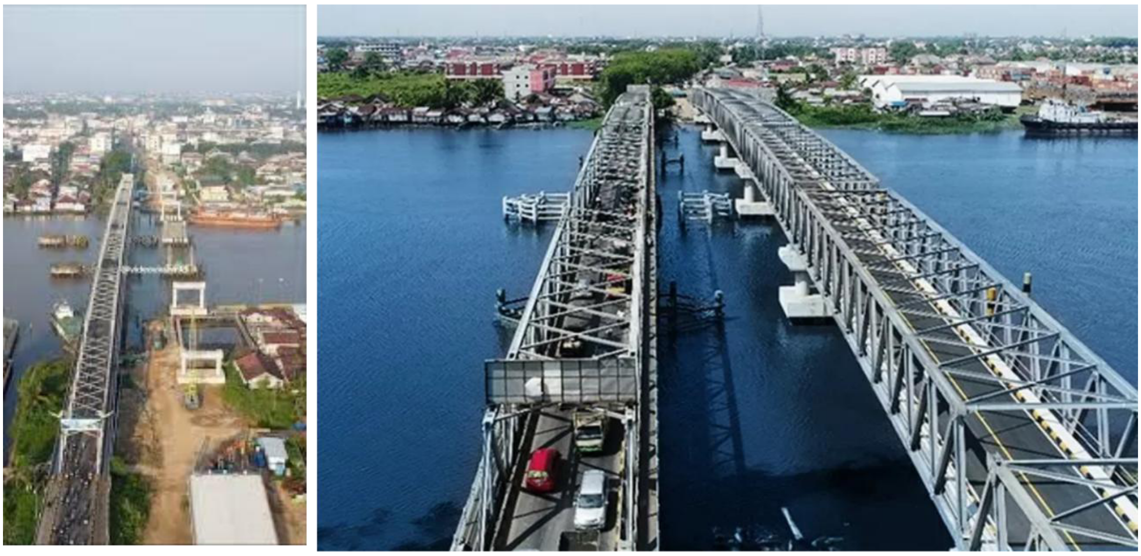

Figure 7.1. Kapuas 1 Bridge in Pontianak

Meanwhile, the integration of life-cycle analysis and socio-economic aspects in structural assessments allows for more sustainable decisions regarding large bridge rehabilitation investments [48]. In addition to the technical aspects, the application of a life-cycle cost model that combines economic, environmental, and social factors helps to comprehensively assess the long-term impact of each structural intervention [49]. Initiatives toward low-carbon infrastructure also encourage the use of environmentally friendly materials and digitalization methods to reduce carbon footprints during construction and maintenance processes [50]. By integrating the principles of structural resilience, material efficiency, and sustainability, the Kapuas 1 Twin Bridge project is a model for the application of best practices in the rehabilitation of long-lived tropical bridges, ensuring reliable urban connectivity while being adaptive to future environmental challenges.

The planning for the repair of the Kapuas 1 Bridge was carried out by considering the existing conditions and the availability of space around the river. The design approach used is a combination of strengthening and rehabilitation. In the reinforcement stage, the steel elements of the bridge that have decreased capacity due to corrosion are reinforced with more plates (steel plate bonding) and a bolted splice system to increase the rigidity and flexural capacity of the main beam. Meanwhile, the repair of concrete elements is carried out by the epoxy injection method to fill the fine cracks, as well as jacketing on the pillars to increase resistance to lateral forces and earthquakes. In addition to physical improvements, the design of the twin bridges on the south side is designed with modern specifications that are adjusted to the SNI 1725:2016 standard regarding bridge loads. The new structure uses a prestressed concrete box girder system with a pile foundation that penetrates the layer of soft clay soil typical of Pontianak. This design takes into account the effect of differential settlement between the old and new bridges so as not to cause inconvenience to users. The integration of old and new designs is a very crucial technical aspect due to the differences in age, materials, and construction technology. The repair process is carried out with a staged construction approach to ensure the sustainability of traffic flow. In the initial stage, detailed inspections and load tests are carried out to determine the actual capacity of the old structure. After that, reinforcement and rehabilitation work is carried out at night or with an open-and-close lane system so as not to cause significant congestion. The use of hydraulic jack equipment is used to temporarily lift the beam during joint repair or bearing pad replacement. The construction work of the twin bridges is carried out in parallel using precast segmental construction technology, where concrete girder elements are molded off-site and then assembled on-site with a post-tensioning system. This method speeds up the execution time and maintains the quality of the construction. The biggest challenge during the implementation was the humid weather conditions and tides of the Kapuas River which affected the temporary stability of the foundation. Therefore, strict logistics and work safety planning is required to prevent accidents or damage due to natural factors.

Planning for the repair of the Kapuas 1 Bridge in Pontianak is carried out through an integrated approach between strengthening and rehabilitation that prioritizes structural resilience, time efficiency, and continuity of traffic flow. The principles used in this project are in line with the recommendations of the international literature on bridge maintenance and life-cycle management, which emphasizes the importance of a combination of steel reinforcement, concrete repair, and digitalization of inspection and maintenance processes to improve the service life of bridges [51]. In the reinforcement stage of steel elements, steel plate bonding and bolted splice joints are used to increase rigidity and strengthen parts exposed to corrosion—a strategy widely applied in modern engineering to repair bridges with old steel structures in humid climates [52]. For concrete elements, the epoxy injection and jacketing method has been shown to be effective in repairing cracks and improving the resistance of columns to lateral forces and seismic activity, as recommended in the life-cycle rehabilitation guide for concrete infrastructure[53]. The new structure in the form of twin bridges on the south side is designed with a prestressed concrete box girder system that refers to the SNI 1725:2016 standard and considers the differential settlement factor typical of Pontianak clay soil. This approach is in line with the concept of restructuring and re-materialization in structural design that combines material sustainability and construction efficiency [54].

The Kapuas 1 Bridge repair project is not only oriented to technical aspects, but also pays attention to environmental and social sustainability. Construction waste from the process of replacing steel and concrete elements is managed through a reuse and recycle system, where some of the used materials are reused for minor work or as filler materials. The use of water-based steel protective paints is also applied to reduce the emission of volatile organic compounds (VOCs). From a social perspective, this project has a significant impact on the mobility of Pontianak residents. During the construction period, temporary traffic management and socialization were carried out to the public regarding the work schedule to minimize disruption of economic activities. After the project is completed, the existence of these twin bridges provides great benefits in reducing travel time, smoothing logistics flows, and improving regional connectivity. With increased capacity, the risk of congestion decreases drastically, especially during peak hours. The Kapuas 1 Bridge repair project also integrates the principles of environmental and social sustainability which have become a new standard in modern infrastructure engineering. One of its main focuses is the management of construction waste through the reuse and recycle approach, which has proven effective in reducing the carbon footprint and volume of wasted materials in similar projects in various countries [55]. Similar practices are also recommended [56] in a study of social sustainability in the road sector, where project management decisions must consider the impact on the mobility and comfort of the surrounding community. The use of water-based steel protective paints is in line with the global construction industry's efforts to reduce VOC emissions and improve occupational safety, as discussed [57] regarding the relationship between quality control, safety, and sustainability in construction projects. In addition, the application of BIM technology in project management also strengthens the efficiency of resource use and monitors sustainability indicators in real time [58]. From the social aspect, the success of the Kapuas 1 project is also determined by traffic management and public communication during the construction period, which has proven to be effective in maintaining economic activities and citizen mobility as emphasized [59] in a study on the application of IoT and digital technology to support the sustainability of smart cities. Once the project is completed, socio-economic benefits are significantly increased through travel time efficiency, increased transportation capacity, and reduced risk of congestion and pollution, supporting the principles of sustainable urban mobility as highlighted in the book Springer Sustainable Cities: Pioneering Approaches to Green Urbanism and Climate Resilience [60]. In engineering, the Kapuas 1 Bridge repair project shows the importance of periodic inspections and preventive maintenance of vital infrastructure. The results of the post-repair evaluation showed an increase in load capacity of up to 25% and a significant increase in structural rigidity. The integration between old and new technologies is successfully carried out through an adaptive design approach that takes into account the field conditions and characteristics of existing materials. An important lesson that can be drawn is the importance of cross-disciplinary coordination between structural, geotechnical, transportation, and environmental experts in large bridge rehabilitation projects. In addition, the use of digital technology such as structural health monitoring systems (SHMS) is recommended to monitor the condition of bridges in real-time, so that potential damage can be detected early and maintenance costs can be minimized. The repair of the Kapuas 1 Twin Bridge in Pontianak is a clear example of the application of holistic road and bridge engineering principles—combining technical aspects, traffic management, and environmental sustainability. Through a twin design approach and modern technology, the project has succeeded in increasing the capacity and safety of the infrastructure without significantly disrupting community activities. The success of this project confirms that the maintenance and rehabilitation of the bridge must be systematically planned as part of the national infrastructure asset management strategy.

The Kapuas 1 Bridge repair project emphasizes the importance of periodic inspections and preventive maintenance in maintaining the integrity of bridge structures that have been operating for a long time in the tropical environment. Post-repair evaluation showed a significant increase in load capacity and structural rigidity, in line with global findings regarding the effectiveness of data-driven maintenance and rehabilitation programs on improving bridge performance [61]. The integration between old and new technologies is carried out through adaptive design that takes into account existing field and material conditions, in line with the digital twin and BIM approach to infrastructure lifecycle management that is now widely applied in large bridge projects [62]. The use of the SHMS allows for real time monitoring of the condition of the structure, supporting early detection of potential damage and minimizing treatment costs [63]. AI-based approaches are also increasingly playing a role in predicting damage and optimizing structural maintenance processes, as explained [64] in his study on AI-based predictive modeling for civil engineering. The integration of disciplines such as structure, geotechnics, transportation, and the environment is the key to the success of large bridge rehabilitation, as shown in the study [65] on the application of cross-sector digital twins for design and maintenance optimization. In the context of national infrastructure asset management, digital data-driven monitoring and adaptive design are assessed as strategic steps to ensure the long-term sustainability of bridge operations [66]. The success of the Kapuas 1 Twin Bridge project reflects a new paradigm of holistic infrastructure engineering—combining digital technology, multidisciplinary coordination, and sustainability strategies to ensure the bridge's safety, efficiency, and long-term durability.

7.4. Integration of Road Engineering with Environmental Engineering

The integration between road engineering and environmental engineering is a modern approach in the development of transportation infrastructure that emphasizes the balance between technical functions and environmental sustainability. Road construction not only aims to provide access and connectivity, but must also ensure that the impact on the ecosystem, air quality, water, and social of communities can be minimized. In this context, environmental engineering plays an important role in every stage of a road project—from planning, construction, to operation—to create infrastructure that is sustainable and adaptive to environmental change.

7.4.1. Principles of Integration in Road Engineering

The integration between road engineering and environmental engineering is a key pillar in sustainable infrastructure development. The environmentally sustainable infrastructure approach requires the application of life cycle analysis to assess the impact from the planning stage to road maintenance, with the aim of reducing carbon footprint and maintaining ecosystem balance. Site analysis is a crucial stage to determine the trajectory that is by the biophysical and social conditions of the environment, as explained [67] that road construction must consider environmental and social indicators so that traffic efficiency does not compromise the sustainability of the ecosystem. The avoid–minimize–mitigate approach is applied in the design of the trase to avoid conservation areas or wetlands, with alternatives such as the implementation of animal corridors and sustainable drainage systems as described [68] in the context of spatial data-based sustainable urban planning. Effective management of natural resources during infrastructure development is also emphasized [69], who highlight the importance of strengthening policy frameworks and EIA in minimizing ecological damage. Furthermore, the concept of nature-based solutions (NBS) as described [66] offers a biomimicry and green infrastructure approach to balance development needs with conservation. Another study highlights the importance of community participation in sustainable infrastructure development. [70] emphasize that the perception and involvement of local stakeholders is an important factor in the implementation of sustainability principles. Green infrastructure approaches in sensitive environments, such as swamp or coastal areas, have also been shown to restore ecosystem function and strengthen landscape identity, as shown in the study [71] on the restoration of the Tacna wetlands. Similar principles are applied in the design of sustainable public spaces in Huancavelica, which suggests that the integration of clean technology and local materials can improve people's environmental awareness [71]. The application of the principle of environmentally sustainable infrastructure in road design not only reduces ecological impacts, but also strengthens social and economic connectivity in a sustainable manner.

7.4.2. Sustainable Water and Drainage Management

The aspect of surface water management in modern road design is a key element in supporting sustainable infrastructure. The increase in watertight surfaces due to road construction has the potential to increase the volume of surface runoff and flood risk, so that the implementation of the Sustainable Urban Drainage System (SUDS) system is an effective solution to maintain natural hydrological balance. A study [72] shows that the application of SUDS based on hydrodynamic modeling in mass transportation projects can significantly reduce the risk of urban flooding through the concept of control-at-source. In addition, the integration between bio-swale systems, porous pavement, and retention ponds has been shown to be efficient in controlling surface runoff and improving water quality, as described [73] in a global study on urban rainwater management. The principle of zero runoff now adapted in urban road design allows rainwater to be absorbed or stored locally, supporting groundwater conservation and preventing flooding in downstream areas, in line with the recommendations of [74] regarding the application of NBS in cold urban regions of Canada. The concept of blue-green infrastructure that emphasizes the balance of ecological and social functions is also the basis for the development of efficient and climate-resilient urban drainage systems [75]. A similar approach in the context of developing countries is highlighted [76], who affirm the importance of adapting sustainable drainage designs based on local conditions and community participation. [77] reinforced these findings with simulation results showing that a combination of large- and small-scale NBS can reduce runoff peaks by up to 32% and increase the capacity of urban drainage systems. Overall, the implementation of the SUDS system and nature-based drainage has proven to be an effective approach in flood mitigation, erosion control, and environmental quality improvement in urban areas.

7.4.3. Pollution Control and Energy Efficiency

The construction and operation of modern roads present challenges related to air pollution, noise, and vibration caused by vehicle activities. Mitigation efforts are now directed at the application of sound-absorbing materials such as low-noise asphalt and the installation of noise barriers in urban areas, which have been proven to be effective in reducing traffic noise levels according to a global study on the sustainability of road infrastructure [51]. In addition, planting buffer vegetation plays a role in absorbing air pollutants and improving the quality of the road environment [78]. Energy efficiency is also an important focus through the implementation of energy-efficient LED-based smart lighting systems that adjust light intensity to traffic volume, as recommended in low-carbon infrastructure research [50]. In the context of reducing carbon emissions, the green road concept is applied through the use of recycled materials such as RAP and geopolymer concrete that suppress emissions from the production of new materials [79]. This approach is in line with climate-resilient infrastructure strategies that emphasize energy efficiency and minimization of construction waste [80]. On the other hand, the application of smart city technology and sustainability-based design has become a common practice in the development of modern urban infrastructure [81]. Furthermore, the development of green roads in urban areas emphasizes the integration between energy efficiency, smart technology, and environmental sustainability as part of long-term planning for sustainable transportation [82]). By combining technological innovation, energy management, and the use of environmentally friendly materials, the principles of sustainable road engineering are now transforming into practices that not only support traffic efficiency, but also protect ecosystems and improve people's quality of life.

7.4.4. Integration at the Policy Scale and Sustainable Development

The integration between road engineering and environmental engineering cannot stop at the project level, but must instead be an integral part of national and regional development policies. The concept of Green Infrastructure and Low Impact Development (LID) needs to be institutionalized in road design standards and regulations to ensure that every transportation project is evaluated through sustainability indicators that include energy efficiency, soil conservation, water quality, and social aspects. The study [83] confirms that the transition to low-carbon infrastructure requires synergy between national policies and the implementation of green technologies, including emission reduction and clean energy management. Sustainability assessment systems also play a crucial role in ensuring that road and transportation projects meet global environmental standards. [84] show that systems such as green roads, Envision, and I-LAST can be adapted for the evaluation of infrastructure projects, especially through decision analysis methods such as

TOPSIS to assess sustainability indicators at the national level. Another study [85] highlights the importance of environmental and social health-based assessment frameworks in the context of historic urban planning, which is relevant to the integration of transportation planning and community well-being. The application of the concept of Green Rating and environmental audits at the local government level is crucial to ensure policy alignment with local conditions. [86] emphasize the need to reorient certification systems toward addressing major issues such as greenhouse gas mitigation and material efficiency, rather than simply meeting minimum standards. A participatory and multidisciplinary approach is also key in developing innovations that are appropriate to the geographical characteristics of developing countries, as conveyed [87], who compared sustainability assessment systems in Germany, the US, and India to find priority indicators in the field of transportation and land use.

Road and bridge engineering is an important field in civil engineering that has a strategic role in supporting mobility, economic growth, and equitable distribution of regional development. Through an understanding of the basic principles of engineering, an engineer is required to be able to design an infrastructure that is not only strong and safe, but also efficient, functional, and in harmony with the conditions of the surrounding environment. This chapter has outlined the various interrelated aspects of the planning and implementation process of road and bridge projects—from basic concepts, topographic and environmental considerations, to case studies and integration with environmental engineering. From the discussion of the basic principles of road and bridge engineering, it can be concluded that every project must begin with a careful analysis of the needs and conditions of the field. Geometric design, structure, and materials must be adjusted to the function of the road, traffic volume, and carrying capacity of the soil. The selection of construction methods and pavement systems is also a determining factor in achieving optimal service life. In the context of bridges, careful planning for loads, stability, and durability to environmental conditions is key to ensuring safety and long-term operational sustainability.

Road design that pays attention to topography and the environment shows the importance of technical adaptation to natural conditions. Diverse topography demands innovative solutions in slope control, drainage systems, and slope stability, while environmental factors demand protection of water, soil, and biodiversity resources. A sustainability-based approach makes road engineering not only function as a means of transportation, but also as part of a spatial layout that is in harmony with its ecosystem. The case study of the repair of the Kapuas 1 Twin Bridge in Pontianak shows the real application of engineering principles in the context of existing infrastructure rehabilitation. The project demonstrates the importance of integration between technical planning, traffic management, and social and environmental impact management. The success of the project confirms that infrastructure modernization does not have to mean replacing completely, but can be achieved through efficient and sustainable adaptive improvements. Finally, the integration between road engineering and environmental engineering is the future direction of transportation infrastructure development in Indonesia. The application of the concept of green roads, sustainable drainage systems, the use of environmentally friendly materials, and community participation reflects the evolution of the civil engineering paradigm toward environmentally and socially sound development. By prioritizing technological innovation, resource efficiency, and ecological responsibility, road and bridge engineering can continue to play a role as a driver of progress while maintaining a balance between human needs and nature conservation.

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CHAPTER 8
ENVIRONMENTAL ENGINEERING AND INFRASTRUCTURE IMPACTS

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Infrastructure development is one of the main drivers of economic growth and improvement of people's quality of life. Roads, bridges, buildings, drainage systems, and other public facilities are the backbone of social and economic activities in various regions. However, behind its vital role, infrastructure development also has consequences for the environment. Construction activities, land use, and increased mobility and urbanization often put pressure on natural ecosystems, reduce air, water, and soil quality, and trigger spatial changes that are not always in line with sustainability principles. In the context of environmental engineering, infrastructure development should be seen not only as a physical process, but as an integrated system that affects ecological and social balance. Therefore, a sustainable approach is an urgent need so that the economic benefits of development are not compensated for by environmental damage that is difficult to recover. Technology, policies, and community participation have an important role to play in ensuring that every infrastructure project runs in line with the principles of environmental conservation.

This chapter discusses various important aspects related to the relationship between infrastructure and the environment. The first section describes the environmental impacts of national road construction, including disturbances to soil, water, air, and biodiversity. The second part reviews environmental impact mitigation strategies that can be implemented to reduce the negative effects of development. Furthermore, the third part presents a case study of waste and air pollution management in urban areas, as a real picture of the challenges and solutions faced by large cities. Finally, the fourth section discusses the role of environmental technology in sustainable infrastructure management, highlighting innovation and the application of green technologies that can support a more environmentally friendly development future. Through an understanding of these four aspects, it is hoped that readers can see that infrastructure development is not only about concrete and asphalt, but also about the balance between human needs and the preservation of nature. Environmental engineering exists as a bridge that connects the two — ensuring that progress doesn't have to be paid for with damage, but rather can go hand in hand toward sustainability.

8.1. Environmental Impact of National Road Construction

National road construction is one of the important elements in efforts to improve connectivity and economic equity in a country. Roads serve as the main means of mobility of goods, services, and people, thereby accelerating regional growth and connecting urban and rural areas. However, behind its great socio-economic benefits, the construction of national roads also has a significant impact on the environment, both at the construction, operational, and post-operational stages. These impacts include land degradation, loss of biodiversity, increased air and noise pollution, and changes in hydrological patterns that can trigger flooding and erosion. In the early stages of development, land clearing and slope cutting activities often cause disturbances to the natural soil structure. Deforestation for road widening leads to reduced forest cover and natural habitats of various species, as outlined [1], who suggests that road infrastructure projects in Eastern Europe significantly increase habitat fragmentation and urban sprawl. The impact is exacerbated in tropical regions such as Indonesia, where erosion and sedimentation rates increase due to heavy rains and steep slopes. A similar phenomenon was also found in road projects in Yunnan, China, which showed that road construction accelerated the degradation of forest ecosystems and drastic changes in land use [2]. Sedimentary material carried by rainwater flows reduces surface water quality and worsens natural drainage capacity. The results of [3] study on the NH-353J project in India show that increased water turbidity and heavy metal contamination are the dominant effects in the area around the national road project. In addition, soil compaction activities and the use of heavy equipment disrupt the groundwater percolation system, which has an impact on decreasing the ability of the land to absorb rainwater and increasing the risk of flooding in downstream areas.

On the other hand, the type of road pavement material also plays a role in the level of pollution. A study [4] found that concrete-based pavement has a higher potential to damage ecosystems and produce greenhouse gas emissions than conventional asphalt, especially through CO_2 and ozone emissions. The study emphasizes that the choice of construction materials must consider a life cycle assessment so that the impact on natural resources and human health can be minimized. From the social and economic aspects, the construction of national roads also have a double effect. On the one hand, increased connectivity drives economic growth, but on the other hand it can trigger uncontrolled urbanization and pressure on ecosystems. This is in line with the findings of [5], who highlight that integrated road-rail infrastructure projects in urban areas are at risk of causing excess land consumption if not balanced with sustainable planning. In addition to the direct ecological impact, the road planning process often does not fully take into account environmental aspects. Research [6] emphasizes the importance of Building Information Modeling (BIM) and traffic simulation approaches in road route optimization to significantly reduce energy consumption and environmental impact. Such a digital approach allows for more precise analysis of topography, traffic, and pollutant emissions over the life of the project. In the context of policy, the use of Sustainability Rating Systems (SRSs) such as CEEQUAL and Green roads has been proposed to assess the sustainability performance of road infrastructure. The study of [7] found that although environmental aspects are already a major concern, the social and economic dimensions still lack proportional weight in the assessment system. These findings show the need to integrate socio-ecological indicators in each stage of road construction so that economic benefits do not come at the expense of environmental sustainability. The research of [1] confirms that sustainable solutions such as green corridors, natural drainage systems, and cliff retaining vegetation need to be part of the national road construction design. This approach is in line with the idea of green infrastructure development that prioritizes a balance between transportation needs and environmental protection. As such, any national road project must be equipped with a thorough environmental impact analysis, the application of modern mitigation technologies, and a commitment to sustainable monitoring so that the benefits of development can be felt without sacrificing the ecosystem and the quality of life of the community.

In terms of air quality, the construction of national roads has the potential to increase motor vehicle exhaust emissions, especially in areas that experience a surge in traffic flow after the road is completed. Pollutants such as carbon monoxide (CO), nitrogen oxide (NOx), sulfur dioxide (SO_2), and fine dust particles (PM10, PM2.5) are major contributors to air pollution around road corridors. This increase in emissions not only reduces ambient air quality, but also has a direct impact on public health along transportation routes. According to [1], new road infrastructure in the Central European region increased NO_2 levels by up to 30% in the first year of operation, which is closely related to the increase in cases of respiratory distress in the surrounding region. Similar results were also reported by [3] in a study on the NH-353J national four-lane road project in India, which showed that the concentration of fine particulate matter (PM2.5 and PM10) doubled during the construction phase compared to the initial ambient values. Increased traffic intensity also triggers noise that disrupts the comfort of residents, where noise levels around major roads can reach 80–90 dB, exceeding the health thresholds recommended by the WHO. According to [8], exhaust emissions and noise are two of the most critical aspects of infrastructure projects in South Asia, with cumulative effects on air quality, microclimate change, and public health. In addition to the impact on the air and humans, road construction also puts serious pressure on ecosystems and biodiversity. Deforestation and the clearing of new trails lead to habitat fragmentation, which is the breakdown of forest areas that were originally intact into small, isolated patches. These conditions inhibit the movement of wildlife and increase the risk of local extinction, especially for species with limited roaming areas. [9] affirm that the existence of roads and their supporting areas can reduce ecological connectivity by up to 60% in some European regions, reducing the ability of ecosystems to provide environmental services such as air filtration and carbon sequestration.

A real case can be seen in South Korea, where dense road networks contribute greatly to increased wildlife-vehicle collisions (WVCs) and loss of vertebrate diversity, especially in Korean water deer and wild raccoon species [10]. Roads that divide conservation areas exacerbate these conditions because they facilitate human activities such as hunting, illegal logging, and forest encroachment. In this context, [9] mention the need for the development of green corridors along roadsides to reduce habitat fragmentation and facilitate animal migration. In addition, the cumulative effects of air pollution from motor vehicles also have an impact on vegetation around the road. [11] explain that the accumulation of heavy metals such as Pb, Zn, and Cd in the soil around the road can decrease plant productivity and affect the balance of microecosystems. Research [12] found that the combination of noise and air pollution from road traffic lowers urban bird populations by up to 40%, due to disruption of their communication and migration patterns. The environmental impact of roads is also twofold: in addition to damaging ecosystems, some construction elements such as road verges or roadsides can provide certain ecological benefits if managed properly. [13] mentioned that roadside vegetation has the potential to provide additional ecosystem services such as air filtration, carbon storage, and habitat for pollinating insects. However, these benefits can only be achieved if they are designed with ecological engineering principles and use native vegetation that is in accordance with the local ecosystem. To overcome this negative impact, a green highway development approach based on GIS and BIM technology has begun to be implemented. According to [11], this combination of technologies allows for precise mapping of sensitive areas and helps design road traces that minimize ecosystem fragmentation. This approach is also used to identify areas at high risk of noise and air pollution so that mitigation can be carried out through noise barriers, dust-retaining vegetation, or environmentally friendly drainage systems. Various studies show that the construction of national roads that do not consider environmental aspects can trigger air degradation, public health problems, and loss of biodiversity. Conversely, if planned adaptively with green technology and conservation approaches, road infrastructure can be developed sustainably without compromising the balance of the ecosystem.

From a hydrological perspective, changes in land use due to road construction affect the dynamics of surface flow and groundwater infiltration. The watertight road surface inhibits the natural seepage process, thereby increasing the volume of rainwater runoff.

When the drainage system is not properly designed, this condition can increase the potential for flooding in the surrounding area and accelerate soil erosion on road slopes. According to [14], the increasing frequency of floods, landslides, and erosion along linear infrastructure such as highways in the Nordic region demonstrates the need for a nature-based solutions (NbS) approach to stabilize drainage systems and increase soil pervasiveness. Similar conditions are also observed [15], who emphasize that extreme rainfall changes due to climate exacerbate the damage to forest road networks and drainage, so that adaptive design based on climate-smart forestry is needed to maintain the ecological and hydrological function of the surrounding area. In tropical and mountainous regions, road construction on steep slopes is at high risk of triggering landslides. A study [16] in Cairo showed that up to 16% of road areas on slopes have high potential for landslides, especially in areas with high rainfall and uncontrolled drainage. In addition to flooding and erosion, runoff from road surfaces often contains oils, heavy metals, and other chemicals that can contaminate surrounding water bodies. Research [17] shows that polluted runoff in the Swat River valley, Pakistan, after major floods worsens groundwater quality due to increased heavy metals such as Pb and Zn that accumulate along transport routes. A similar phenomenon was also discovered in India [18], who explained that disturbances in natural hydrology due to road construction in the Himalayan region lead to a significant increased risk of flash floods and sedimentation of water bodies.

Geomorphological aspects also play an important role in understanding the impact of hydrology. A study [19] in Nigeria showed that the increase in built-up area due to road construction alters drainage density and disrupts the stability of soil structures, thereby increasing the risk of inundation and decreased infiltration capacity. Cross-border studies show a consistent pattern: the wider the network of roads and watertight areas, the greater the pressure on the local hydrological system. This hydrological impact then spreads to the social and economic dimensions. Increasing accessibility through the construction of national roads can accelerate urbanization and conversion of agricultural land into residential or industrial areas. According to [20], changes in land cover due to infrastructure development in the district of Kohistan, Pakistan, strengthen the relationship between socio-economic pressures and vulnerability to hydrometeorological disasters such as floods and landslides. Similar conditions were reported in the tropics [21], who found that weak integration between road planning and watershed management increases flood intensity and worsens the balance of local ecosystems. The construction of national roads cannot be seen as a mere physical project, but as a complex and multidimensional spatial transformation process. Changes in water, soil, vegetation, and human activities interact with each other to form new environmental systems that require adaptive management. Therefore, every road construction project needs to be equipped with a comprehensive

Environmental Impact Assessment (EIA), covering physical, biological, and socio-economic aspects in an integrated manner. Mitigation efforts based on nature-based engineering, green drainage, and adaptive spatial planning must be implemented not only to reduce the risk of floods and landslides, but also to ensure the sustainability of ecosystems and community welfare in the future.

8.2. Environmental Impact Mitigation Strategy

The environmental impact mitigation strategy is a systematic effort to reduce ecosystem damage due to the construction of national roads. Modern mitigation approaches now emphasize ecology-based planning, which starts from the project design stage to the operational phase. According to [22], the implementation of a structured mitigation strategy is able to reduce the risk of disturbance to wildlife through adjustments to road design, the construction of animal crossing routes, and intensive supervision of areas prone to human-animal conflict. In the context of geotechnical and construction, sustainable practices such as the use of recycled materials, bioengineering techniques, and vegetation-based soil stabilization systems have been proven to reduce the impact of erosion and extend the life of infrastructure. [23] assert that the use of local materials and environmentally friendly techniques also reduces carbon emissions and road maintenance costs in the long run. The GIS-based spatial approach is an important tool in determining road trajectories that minimize ecological disturbances. [24] showed that environmental mapping and impact assessment based on Leopold matrix are effective in evaluating alternative routes that cause the least disturbance to productive land and protected areas. Meanwhile, [25] emphasizes the importance of integrating sustainable land use policies to control uncontrolled urbanization due to transportation infrastructure development in hilly areas. The mitigation aspect also includes the protection of vulnerable aquatic and terrestrial ecosystems. [26] underscore the importance of implementing a circular economy and conservation of small aquatic ecosystems such as ponds and swamps as part of ecological compensation efforts around large infrastructure projects. This approach is in line with the principle of avoid–minimize–restore–offset, where any unavoidable damage must be compensated through environmental rehabilitation or restoration.

From a geohazard perspective, the book The Himalaya Dilemma [27] emphasizes the importance of mitigating disaster risks such as landslides and erosion in steep topographic areas. Proper drainage systems, vegetated retaining walls, and continuous spatial monitoring are integral to the design of disaster-resilient infrastructure. Meanwhile, [28] emphasize the importance of a balance between coastal development and the conservation of adjacent wetlands, with a collaborative approach between local governments and communities to avoid environmental degradation. This overall mitigation strategy reflects the need for cross-disciplinary and cross-sectoral synergy. Technical, ecological, and social approaches must be integrated so that national road construction is not only economically efficient, but also resilient to environmental and social changes. Thus, the application of erosion control technology, high-standard construction waste management, and ecological compensation based on spatial data are key steps towards the development of truly sustainable road infrastructure.

In addition to the physical aspect, noise and air pollution mitigation is also an important part of the sustainability strategy in the construction of national roads. The use of heavy equipment with low emission standards and the application of Internet of Things (IoT)-based air monitoring technology has been proven to be able to reduce the concentration of pollutants such as NO_2, CO, and $PM_{2.5}$ around construction projects. Artificial intelligence (AI)-based approaches to pollution monitoring have now been widely applied in the infrastructure sector to accelerate air pollution detection and control, as described [29] in AI-Driven Environmental Pollution Management. Noise mitigation can be done through the design of acoustic barriers in densely populated areas as well as the limitation of heavy equipment working time, as outlined in the Handbook of Construction Project Management by [30], which emphasizes that the integration of green construction principles and noise control is an important element in modern project management. Continuous monitoring of air quality and noise must also be carried out to ensure that pollutant levels remain below the standard threshold of environmental quality. The use of an environmental management system based on the ISO 14001 standard is recommended [31] as a framework to ensure the operational sustainability of transportation infrastructure.

At the operational stage, mitigation strategies are focused on long-term management of air, water, and biodiversity quality. Greening along road corridors (green belts) is the most effective natural method in reducing carbon emissions and noise. According to [32] in Rethinking Sustainability Towards a Regenerative Economy, road vegetation can act as an ecological buffer that helps the absorption of air pollutants while stabilizing micro temperatures in urban areas. Eco-friendly drainage systems such as bio-swales and porous asphalt have also begun to be developed as they increase groundwater infiltration and reduce runoff, as studied in Clean Water and Sanitation [33] which emphasizes the integration of clean water technology in the construction of road infrastructure. Biodiversity mitigation is also an integral part of sustainable infrastructure development. The construction of wildlife crossings such as ecological bridges and underpasses has proven effective in reducing habitat fragmentation and animal accidents on highways. A study summarized in the Handbook of Global Sustainability [34] shows that infrastructure projects with animal trajectory facilities can increase ecosystem connectivity by up to 60% in terrestrial conservation areas. In addition, the rehabilitation of ex-excavated land through revegetation using local species helps restore ecological function and prevent the invasion of foreign species. The social aspect of environmental mitigation is no less important. Local community participation in project oversight and maintenance of green spaces has been shown to increase mitigation effectiveness by up to two-fold. According to [35], a collaborative approach between the government, contractors, and the community strengthens environmental justice and expands the positive impact of development on the quality of life of local residents. The application of an adaptive-based Environmental Management System (EMS) ensures that any changes in environmental conditions can be immediately responded to through continuous strategy improvement.

8.3. Waste and Air Pollution Management in Urban Areas

Urban areas are the center of dense economic, industrial, and transportation activities, making them a major contributor to waste generation and air pollution. Rapid population growth is accompanied by increased energy consumption and waste production, which has direct implications for the deterioration of environmental quality. As revealed [36], the increase in the volume of waste in the city of Tabuk, Saudi Arabia, triggers large amounts of methane (CH_4) and carbon dioxide (CO_2) emissions due to organic decomposition at landfills. These gases are a major contributor to global warming and urban air pollution. Similar conditions are occurring in many major cities in developing countries, including Indonesia, where rising solid waste and weak management systems exacerbate air and groundwater pollution. Solid waste management in urban areas is still a major challenge for many cities in the world. A study [37] shows that in most cities in the Global South, waste management that is not separated between domestic and hazardous waste leads to soil and water contamination, as well as poses a serious public health risk. To overcome this, the circular economy approach and the principle of zero waste are solutions that are increasingly adopted globally. For example, research [38] on the Canadian system shows that synergies between policy, technology, and community participation can reduce waste by up to 60% through Extended Producer Responsibility (EPR) schemes and color-based sorting. The 3R (reduce, reuse, recycle) program implemented in many developing cities has proven effective in reducing waste generation and greenhouse gas emissions. The results of a study [39] in China show that the use of biochar and organic fertilizers from waste treatment can reduce carbon emissions by up to 59% and increase economic efficiency by 135% compared to conventional systems. This approach is relevant for big cities such as Surabaya or Bandung, where the integration of compost and biogas from organic waste has shown positive results in reducing methane emissions and extending the life of landfills.

In addition to solid waste, air pollution is a major environmental issue in urban areas. According to [40], the implementation of circular economy policies in the United States contributes significantly to reducing air pollutants, especially fine particles ($PM_{2.5}$), through increased recycling and reduced fossil energy consumption. On the other hand, increasing population density and the number of motor vehicles remain the dominant factors in worsening air quality. The WHO notes that chronic exposure to $PM_{2.5}$ can increase the risk of cardiovascular and respiratory diseases by up to 30% in high-polluted urban areas. In various parts of Africa, similar problems are faced due to increased industrial and transportation activities. [41] show that most African urban waste is made up of 60–80% organic material that has the potential to produce high methane if not managed separately. Therefore, the development of Material Recovery Facilities (MRF) is considered an adaptive solution to reduce dependence on landfills and reduce urban carbon emissions. Air pollution management strategies also include the control of short-lived climate pollutants (SLCPs) such as black carbon and tropospheric ozone. A study [42] using life cycle analysis (LCA) on waste management systems in Semarang shows that SLCP emissions from open combustion and decomposition processes can be reduced by up to 40% through the improvement of logistics systems and material-based waste sorting. In the context of transportation policies, many cities are beginning to adopt transition strategies towards low-emission mobility. This includes the development of electric public transportation, bicycle lanes, and the implementation of digital sensor-based air monitoring systems to provide real-time data to the public. This kind of integrative approach is in line with the recommendations of [40], who affirm that cross-sector collaboration is key to achieving sustainable urban air quality. Waste and air pollution management in urban areas must be carried out holistically through policy synergy, technological innovation, and community participation. These efforts not only reduce emissions and improve environmental quality, but also strengthen the city's resilience to climate change.

Modern technological approaches to waste and air pollution management in cities are now the main foundation towards smart and sustainable cities. One of the important innovations is waste-to-energy (WTE), which is a technology that converts solid waste into electrical energy through a controlled thermal process with an emission filtration system. Studies show that the integration of WTE in waste management systems can significantly reduce waste volume by up to 90% and produce sustainable alternative energy sources, while reducing dependence on landfills [43]. Despite the high initial investment costs, the successful implementation of WTE in developed countries shows that this approach is a long-term solution to the urban waste crisis [44]. In addition, smart air monitoring technology has become an important part of the city's environmental management system. Internet of Things (IoT)-based air sensors enable real-time monitoring of air quality and rapid response to extreme pollution conditions. The integration of these systems within the framework of smart city policies is able to accelerate mitigation measures such as traffic restrictions, industrial control, and low-carbon transportation planning [45]. In this context, the application of artificial intelligence (AI) for predictive analysis further improves the accuracy and efficiency of environmental policies, strengthening the resilience of cities to pollution and climate change risks [46]. The concept of smart and green city also emphasizes the importance of utilizing renewable energy, environmentally friendly materials, and electric transportation systems to reduce carbon emissions in urban areas [47]. Modern smart cities dynamically leverage environmental data to support evidence-based decision-making, including in waste management and low-emission public transport [48]. The merger of WTE technology, smart air monitoring systems, and AI-based management creates a strong synergy between energy efficiency and environmental conservation. This emphasizes that the success of waste and air pollution management in urban areas is highly dependent on the integration of smart technologies, adaptive policies, and the active participation of the community in maintaining the sustainability of future cities [49].

8.4. Environmental Technology for Sustainable Infrastructure Management

Sustainable infrastructure development is a major challenge in the modern era, when the need for economic progress must be balanced with environmental conservation. In the context of environmental engineering, technology plays an important role in minimizing negative impacts and optimizing resource efficiency. This approach is known as clean technology or green technology, which emphasizes the efficient use of resources, minimal waste, and the application of circular economy principles throughout the infrastructure life cycle. According to [50], the application of circular economy principles in the construction sector requires urban mining, material passports, and the use of Building Information Modelling (BIM) to monitor the life cycle of materials and support adaptive green building design. One of the prominent applications of environmental technology in sustainable infrastructure management is the use of environmentally friendly materials. [51] confirms that porous concrete, green concrete, and the use of additives such as fly ash or industrial slag significantly reduce carbon emissions and increase rainwater absorption, thereby reducing surface runoff and flood risk. Another study [52] also shows that innovations in pavement technology, such as recycled asphalt pavement and biomass-based cold asphalt, can extend the life of roads while reducing carbon footprints by up to 30% compared to conventional systems. In addition, the use of alternative materials such as geotextiles in the manufacture of pavement blocks and bus station pavements also shows great potential in increasing structural resilience while reducing cement consumption, which is known to be a major source of CO_2 emissions for the construction industry. [53] proved that geotextile-based paver blocks with a mixture ratio of 40–60% are able to increase compressive strength by up to 36 N/mm^2 and reduce the environmental footprint compared to ordinary concrete.

In the context of digitalization, smart infrastructure is an important breakthrough to improve operational efficiency and monitoring environmental conditions. Sensor technology and the Internet of Things (IoT) are now being applied to monitor air quality, road structure conditions, and drainage systems in real-time. These systems can send data directly to the control center to support quick decision-making, for example in the management of floods or air pollution. The integration of artificial intelligence (AI) and machine learning (ML) has also strengthened the capabilities of predictive analytics in sustainable infrastructure management, such as early detection of road damage and monitoring of carbon emissions [54]. On the other hand, the concept of renewable energy in infrastructure is increasingly prominent, especially with the implementation of solar-based public street lighting systems and smart grids. [55] highlight that the application of photovoltaics and piezoelectric technology on highways can generate electrical energy from sunlight and traffic vibrations, making it a dual solution for transportation and clean energy. In addition, the green building concept also plays a central role in reducing energy consumption through natural ventilation design, the use of LEDs, and the integration of solar panels and rainwater recycling systems. The role of smart and digital technologies in sustainable development was also emphasized by the ICRES 2025 conference, which promotes resource efficiency through the integration of renewable energy, waste management, and green supply chains to achieve a circular economy [56]. With these advances, infrastructure development is not only aimed at improving connectivity and the economy, but also ensuring ecological balance through the utilization of environmentally friendly technologies, energy efficiency, and data-driven adaptive systems.

Wastewater treatment technology is also a crucial aspect of sustainable infrastructure management. Modern wastewater treatment systems now use many biological technologies such as membrane bioreactors (MBR), constructed wetlands, and moving bed biofilm reactors (MBBR). These technologies are capable of treating domestic and industrial waste with high efficiency, producing treated water that can be reused for irrigation, garden watering, or industrial purposes. In dense urban areas, the decentralized wastewater treatment system (DEWATS) is an efficient alternative solution because it can be built on a small scale at the community level without the need for large land. In addition to water, solid waste management is also advancing thanks to technological innovations. The automatic waste sorting machine is able to separate waste types based on materials through optical and electromagnetic sensors, speeding up the recycling process. Bioconversion technology uses microorganisms or insects such as black soldier flies to convert organic waste into fertilizer and animal feed. Modern wastewater treatment technology plays a central role in realizing sustainable infrastructure that is environmentally friendly. Systems such as membrane bioreactors (MBRs) and moving bed biofilm reactors (MBBR) have been proven to improve the efficiency of organic matter and nitrogen removal compared to conventional systems, while producing treated water that can be reused for non-potable purposes such as irrigation and landscape engineering [57]. In dense urban areas, decentralized wastewater treatment systems (DEWATS) are an effective solution because they save land and energy, and support community-based water management [58]. In solid waste management, innovations such as automated waste sorting and bioconversion using black soldier fly have shown high efficiency in converting organic waste into new resources, including fertilizers and animal feed [59]. Waste-to-energy (WTE) technology through gasification and pyrolysis is also a global trend in energy conversion from solid waste to controlled emissions [60].

On the other hand, the development of waste-to-energy (WTE) based on controlled incineration, gasification, or pyrolysis continues to be developed to convert waste into energy without producing harmful emissions. This innovation shows that waste is no longer just a problem, but can become a new resource when managed with the right technology. The application of environmental technology also includes the use of data-driven monitoring and management systems. The concept of Building Information Modeling (BIM) and Geographic Information System (GIS) is an important tool in environmentally friendly infrastructure planning. BIM allows building design simulations to minimize material and energy use, while GIS helps analyze environmental impacts based on geographical conditions. Both technologies facilitate more accurate and sustainability-oriented decision-making from the early stages of the project. However, the success of the application of environmental technology does not only depend on the availability of the technology itself, but also on institutional, regulatory, and user awareness aspects. Policies that encourage investment in green research and innovation, as well as incentives for industries and the construction sector that apply environmentally friendly technologies, are needed. Education and training for workers in the field of environmental engineering are also important so that technical skills are in line with technological advances. Without consistent human resource support and policies, technological innovation is difficult to have a real impact on sustainability. Environmental technology is the main foundation in efforts to build efficient, resilient, and sustainable infrastructure. By combining the principles of eco-friendliness, digital innovation, and social awareness, development can not only meet current needs but also maintain the balance of the ecosystem for future generations.

Table 8.1. Logical Framework Matrix Environmental Engineering and Infrastructure Impact

Hierarchy of Objectives	Verifiable Indicators	Methods of Verification	Assumptions and Risks
GOAL (Final Goal)	The realization of sustainable national infrastructure development, environmental resilience, and energy efficiency.	Sustainable national development reports, national emission data, reports from the Ministry of PUPR & MoEF.	Political support and green development policies remain consistent; economic stability and investment climate are maintained.
OUTCOME (Hasil Antara)	- Reduction of CO_2 emissions and urban air pollutants (PM2.5, NOx, SO_2). - Increase in the use of recycled materials and renewable energy in infrastructure ≥50%. - Implementation of environmental management systems (ISO 14001) in national strategic projects.	Environmental data (MoEF), EIA monitoring report, evaluation of infrastructure projects.	Effective implementation of green policies; cross-sector support (government, private, community).
OUTPUTS (Live Output)	- Environmental impact analysis document for national road construction. - Mitigation and conservation action plan based on *the principle of avoid–minimize–restore–offset*. - Technology-based urban air pollution and waste management model. - Green technology blueprint for sustainable infrastructure (BIM, GIS, IoT, MBR, WTE).	Research reports, case study results, EIA technical documents, reports from related ministries/institutions.	Cross-agency collaboration is effective; data availability and access to adequate research.
ACTIVITIES (Main Activities)	Sub-Chapter 1: Analysis of the impact of national road construction on land, air, hydrology, and biodiversity. Sub-Chapter 2: Identify mitigation strategies at the planning, construction, and operational stages of infrastructure. Sub-Chapter 3: Case study of waste and air pollution management in big cities with a 3R approach and green transportation. Sub-Chapter 4: Application of environmental technology (green materials, BIM, GIS, MBR, WTE, IoT, solar street lighting).	Activity reports, observation results, field data, scientific publications, stakeholder interviews.	Technical support and funding are available; The community's adaptation to new technologies is going well.
INPUTS	- International scientific data and literature (2020–2025). - National regulations and EIA guidelines. - Environmental technology (MBR, WTE, BIM, GIS, IoT). - Environmental engineering experts and institutional support.	Dimensions.ai database, Ministries/Institutions policies, research results and pilot projects.	Funding for sustainable research; adequate technical workforce training; collaboration between academia and active industry.

Source: Author analysis, 2025

Green technology-based infrastructure management is a tangible form of the evolution of environmental engineering towards a cleaner, smarter, and highly competitive future. Digital approaches such as Building Information Modeling (BIM) and Geographic Information System (GIS) are now integrated into green infrastructure planning. BIM enables simulation of energy and material consumption to lower the carbon footprint of projects [61], while GIS is used to map environmental impacts and determine the location of infrastructure with the least ecological disturbance. However, these technological advances will not have a significant impact without regulatory support, green investment policies, and strengthening the capacity of human resources. Recent research emphasizes the importance of integrating public policy with technological innovation in ensuring the implementation of effective sustainable infrastructure practices. Environmental technology is a key pillar in building infrastructure systems that are resilient, efficient, and adaptive to climate change.

The Logical Framework in Chapter 8 is compiled to illustrate the relationship between infrastructure development, environmental impacts, and the application of green technology as an effort towards sustainable development. The construction of national roads and other infrastructure not only impacts improved economic connectivity, but also brings ecological risks such as land degradation, air pollution, hydrological changes, and biodiversity decline. Therefore, a systematic framework is needed to ensure that every stage of development, from planning to operational, takes into account environmental aspects comprehensively. This logical framework integrates the four main components discussed in Chapter 8, environmental impact analysis of national road construction, environmental impact mitigation strategies, case studies of waste and air pollution management in urban areas, and the application of environmental technology in sustainable infrastructure management. Each component is interrelated and forms a logical flow from inputs, activities, outputs, to outcomes and final goals. This approach emphasizes the importance of using environmentally friendly technologies such as membrane bioreactors (MBR), waste-to-energy (WTE), Building Information Modeling (BIM), Geographic Information Systems (GIS), and Internet of Things (IoT)-based monitoring systems to improve energy efficiency and reduce the negative impacts of development on the environment. At the operational level, this logical framework helps explain how mitigation activities and technological innovations can produce concrete outputs, such as mitigation plan documents, environmental monitoring systems, and integrated urban waste management models (Table 8.1.).

These outputs are expected to have an impact on improving air and water quality, energy efficiency, and biodiversity conservation. More broadly, the resulting outcomes contribute to the achievement of national goals in the form of resilient, adaptive and sustainable infrastructure development. This logical framework also highlights the importance of multi-stakeholder engagement—government, academia, the private sector, and society—at every stage of implementation. The basic assumptions underlying the successful implementation of this log frame include consistent policy support, the availability of research and technology funds, and increased public awareness of the importance of environmental conservation. Meanwhile, risks that need to be anticipated include changes in policy priorities, limited human resources, and social resistance to new technologies such as WTE systems and decentralized waste treatment. This logical framework is a strategic guideline to direct the development of environmental engineering in the context of national infrastructure development. With the implementation of this framework, it is expected that every infrastructure project is not only oriented towards economic efficiency, but also pays attention to ecological balance and long-term social sustainability.

Infrastructure development is an important foundation for the progress of a nation, but environmental sustainability must remain a top priority in every stage of its implementation. Through the study in this chapter, it can be seen that every development project, especially national roads and urban facilities, has the potential to have a significant impact on the ecosystem, both physically, biologically, and socially. Therefore, the environmental engineering approach acts as a controller and balancer so that the development carried out does not cause long-term damage to the environment. A well-planned mitigation strategy, effective waste management, and air pollution control are key steps in maintaining environmental quality in the midst of development. In addition, advances in environmental technology provide a great opportunity to create a more efficient, smart, and environmentally friendly infrastructure system. Innovations in construction materials, waste treatment systems, and digital-based environmental monitoring show that sustainability can be achieved without hindering economic growth. However, the success of the implementation of sustainable development does not only depend on technology and policies, but also on public awareness and active participation. Synergy between the government, the private sector, academia, and the community is a determining factor in maintaining a balance between progress and sustainability. Environmental engineering is not just a supporting field, but a strategic element in realizing resilient and sustainable infrastructure development. Through the application of environmentally friendly principles, development can continue to go hand in hand with efforts to preserve nature, creating a clean, healthy, and resilient future for future generations.

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CHAPTER 9

TRANSPORTATION ENGINEERING AND HIGHWAYS

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Transportation plays an important role in supporting economic, social, and regional development activities. Without an efficient and reliable transportation system, the flow of goods and human mobility will be hampered, thus hindering productivity growth and equitable development. In Indonesia, the role of transportation is increasingly crucial due to diverse geographical conditions, ranging from archipelago, mountains, to inland areas, that demand an adaptive and sustainable approach to transportation techniques. In this context, transportation engineering and highway construction function not only as a physical means of movement, but also as a strategic infrastructure that connects the centers of production, consumption, and economic growth. As a branch of civil engineering, transportation engineering studies the principles of planning, designing, and managing transportation systems in order to achieve a balance between efficiency, safety, and comfort. Highway infrastructure is the main backbone of the land transportation system, connecting various regions and supporting people's economic activities. However, as vehicle growth increases, urbanization, and changes in mobility patterns, new challenges arise such as congestion, declining road service levels, and increasing environmental impacts due to transportation. Therefore, a thorough understanding of the basic principles of transportation engineering and proper traffic analysis methods is required.

This chapter discusses four main aspects that are interrelated. First, the basic principles of transportation engineering, which explain the concepts of efficiency, safety, sustainability, and multimodal integration as the foundation of the modern transportation system. Second, traffic analysis and road service levels, which examine how vehicle flow and service quality can be measured and improved through scientific approaches. Third, the relationship between transportation techniques and agricultural business systems, which shows how road infrastructure plays an important role in strengthening the supply chain of agricultural products and improving the welfare of rural communities. Finally, a case study of optimizing the distribution of goods in Kalimantan, which provides a real picture of the application of transportation engineering principles in facing geographical and logistical challenges in central Indonesia. Through the discussion of these four topics, it is hoped that readers can understand that transportation is not only a technical problem, but also a complex socio-economic system. The application of appropriate transportation techniques will encourage more inclusive regional growth, strengthen national connectivity, and realize sustainable development that favors people's welfare.

9.1. Basic Principles of Transportation Engineering

Transportation is one of the main foundations in the social and economic development of a region. Without an efficient transportation system, the distribution of goods and human mobility will be hampered, which ultimately decreases people's productivity and quality of life. Transportation engineering, as a branch of civil engineering, focuses on planning, designing, developing, and managing transportation infrastructure in order to achieve a safe, efficient, comfortable, and sustainable movement system. The basic principles include an understanding of the relationship between humans, vehicles, and roads as a dynamic system that must be optimized technically and socially. One of the fundamental principles in transportation engineering is the efficiency of movement. Every transportation system must be able to move people and goods from one point to another with minimal time, cost, and energy without compromising safety. According to [1], the new paradigm in traffic engineering now emphasizes the balance between efficiency and fairness in the distribution of mobility resources, as efficiency-only systems can create inequality of access for road users.

Transportation efficiency is also closely related to traffic flow control and road capacity. [2] developed a "cooperative vehicle sorting" model for connected automated vehicles that is able to optimize vehicle movement collaboratively and minimize total travel time. This approach shows that digital coordination between vehicles can increase movement efficiency by up to 30% compared to conventional systems. In the context of transportation safety, [3] show that improving vehicle operational efficiency cannot be separated from the management of technical conditions and fleet safety, especially in long-distance freight and passenger transportation. This aspect of safety is an important requirement so that efficiency is not achieved at the expense of the safety of road users. Meanwhile, the concept of sustainable transportation has become a major focus in modern urban development. According to [4], the success of transportation systems is not only measured by speed and capacity, but also by its impact on the environment and urban quality of life. They emphasized that sustainability indicators such as low emissions, energy efficiency, and integration of public transport modes should be an integral part of road network planning. Increased efficiency also depends on the application of digital technology and intelligent monitoring systems. [5] show that geosignal monitoring systems can be used to observe the stability and safety of transportation networks through low-frequency radio signals that detect the movement of objects in real time. Technology like this opens up huge opportunities for data-driven traffic management. In addition, in the context of operational efficiency, the principle of lean engineering that was previously widely used in the manufacturing industry is now also applied to the transportation sector. [6] prove that the application of lean principles can increase productivity by up to 20% by reducing waste in production processes and logistics. A similar concept is applied [7], who show that optimizing material flow and reducing inefficient displacement can improve the efficiency of industrial transportation systems. The green and lean transportation approach is also strengthened in the study of [8], which highlights the importance of energy efficiency and waste reduction in the entire transportation logistics chain, including in the shipping sector. This shows that increasing efficiency must always be accompanied by environmental responsibility, in line with the green transportation development agenda. Efficiency in transportation engineering not only means shortening time and keeping costs down, but it also involves a balance between speed, safety, fairness, and environmental sustainability. Modern transportation planning must integrate the principles of systems engineering, digital technology, as well as social ethics in one comprehensive framework to achieve a truly efficient and humane mobility system.

The second principle in transportation engineering is safety and security. Land transportation, especially highways, is one of the sectors with the highest risk of accidents that cause material losses and fatalities. In the context of modern transportation engineering, safety is measured not only from accident statistics, but also from the quality of the road's geometric design, surface conditions, the layout of signs and markings, and driver behavior. The application of safety principles must begin from the planning stage, including determining the minimum turning radius, stopping visibility, and design speed according to road functions. As shown [9], the predictive safety modeling approach with the Interactive Highway Safety Design Model (JCI) is able to identify high-risk road segments and significantly reduce the number of accidents through precise geometric engineering. The principle of safety is now also evolving towards the concept of safety by design, which is an approach that places the protection of vulnerable users—such as pedestrians and cyclists—as a top priority. The book Safe and Sustainable Mobility by Design [10] emphasizes that pedestrian-friendly city design and public transportation integration are the most effective strategies in reducing accidents while improving air quality and public health. Technological advances also play a big role in improving transportation safety. [11] introduced ScooterLab, a micromobility research platform equipped with sensor and intelligent communication systems to collect traffic data, detect potential hazards, and support the development of data-driven safety policies. This approach illustrates how artificial intelligence and the Internet of Things (IoT) can be critical components in creating safer and more responsive transportation systems. In addition to the human and technological aspects, materials and construction are also the focus of modern safety. [12] show that resonant rubblization technology on road pavements improves structural stability and reduces the risk of road failure by up to 30%, while extending the service life of infrastructure. While [13] highlight the potential of additive manufacturing (AM) in the manufacture of high-performance safety fences and road markings that are able to absorb impact energy more effectively and reduce the impact of accidents.

The third principle in transportation engineering is environmental sustainability. Modern transportation systems must consider ecological impacts such as carbon emissions, noise, and land degradation. Innovations towards environmentally friendly transportation are also seen in the research of [14], who introduced vehicles with piezoelectric transducer-based self-propelled power systems and regenerative braking to reduce dependence on fossil fuels. Approaches like this reflect a new direction of sustainable vehicle development that supports energy efficiency and user safety. In the urban context, [15] through a policy study in Western Australia affirmed the importance of integrating the "Vision Zero" principle in regional transport policies to realize safe and sustainable mobility. This approach emphasizes community engagement, policy clarity, and the ability of local institutions to adapt global safety principles to the city level. Safety and sustainability are inseparable in the design of modern transportation systems. Efforts to improve safety must go hand in hand with reducing environmental impact through pedestrian-friendly road design, the use of green technology, and inclusive smart transportation policies. The integration of engineering safety, technological innovation, and ecological sustainability is the basis for an efficient, safe, and future-oriented mobility system.

The next principle in transportation engineering is accessibility and connectivity, two fundamental aspects that determine the success of a regional mobility system. Accessibility ensures ease for people to reach centers of economic, social, and cultural activities, both in urban and rural areas. The study [16] shows that the efficiency of public transportation networks is highly dependent on spatial and functional integration between modes, where cities with well-connected transportation centers show an increase in travel efficiency of up to 30%. This principle of accessibility is also affirmed [17], who emphasize the importance of "first and last mile" connectivity in the development of transit-oriented development (TOD) as a key factor in the sustainability of urban transportation. Transportation connectivity is not only related to road networks, but also synergy between various modes. In the context of multimodality, [18] show that the integration of air-rail integrated services (ARIS) can improve passenger satisfaction and cross-modal travel efficiency through synchronization of schedules and integrated ticketing systems. Similarly, the study of [19] highlights the importance of mobility hubs in smart cities that integrate public transportation, carsharing, and electric bicycles, in order to reduce carbon emissions and congestion in congested areas. Accessibility is also the main factor in supporting equitable development between regions. [20] emphasized that the incorporation of public transportation networks with bike-sharing systems can overcome limited access in areas with limited transportation infrastructure, especially for low-income groups. On the other hand, [21] developed a GIS-based spatial model to determine the location of intermodal hubs in Bangkok, which has been shown to increase the range of transportation access by up to 20% and reduce mobility inequality between regions. The principles of economic efficiency and resource optimization in transportation development are the main challenges in the era of rapid urbanization. The use of a value engineering approach allows planners to choose the best combination of cost, performance, and infrastructure lifespan. As shown [22], improving port connectivity through multimodal optimization significantly reduces logistics costs and travel time for the distribution of goods by 25%, which has direct implications for regional economic competitiveness. These findings are in line with a global study on port connectivity optimization which concluded that investment in multimodal nodes results in a faster return on investment than increasing single-road capacity. From a social sustainability perspective, accessibility also includes equality for all groups of people, including people with disabilities and the elderly. The universal design approach and the integration of digital technology are strategic steps to expand the range of public transportation access in various geographical conditions. Although still facing limitations, [23] research proves that the use of the Mixed-Integer Linear Programming (MILP) optimization algorithm is able to increase the efficiency of travel routes by up to 20% while expanding transportation inclusivity in community-based tourist destinations. The principles of accessibility, connectivity, and economic efficiency are the main foundations in creating a just and sustainable transportation system. Multimodal integration is not only a technical solution, but also a socio-economic strategy that strengthens inter-regional relations and optimizes the use of public resources. In the context of an archipelagic Indonesia, the development of an integrated transportation network—between land, sea, and air—is a strategic step to improve national connectivity and promote equitable development.

9.2. Traffic Analysis and Road Service Level

Traffic analysis is one of the main components in transportation engineering that serves to understand how vehicle and human movements occur on the road network. Through this analysis, transportation engineers can assess the performance of a road, determine optimal capacity, and design effective traffic management policies. The essence of traffic analysis lies in trying to balance between travel demand and road capacity. When demand exceeds capacity, congestion arises, a classic phenomenon that shows an imbalance between the flow of vehicles and the ability of the infrastructure to serve them. Modern traffic analysis is rooted in the fundamental concept of the diagram of traffic flow, which describes the relationship between vehicle volume, speed, and density. According to [24], the Gaussian Process (GP)-based approach provides a more accurate representation of these dynamic relationships, as it is able to capture the variability of driver behavior and road conditions in various times and locations. This diagram explains that in the initial conditions, increased vehicle volume still allows for high speeds; But once the tipping point is reached, any increase in volume actually causes a drastic decrease in speed. At the scale of urban networks, the macroscopic relationship between flow and traffic density is depicted through a Macroscopic Fundamental Diagram (MFD). [25] explains that MFDs provide a quantitative framework to understand the transition between uncongested and congested conditions, as well as being an important tool for evaluating the operational efficiency of road networks in aggregate. Recent research [26] also introduced an MFD calibration method based on uncertainty quantification, which allows transport planners to assess network capacity by considering empirical variability and system resilience to congestion. The development of Connected and Autonomous Vehicles (CAV) technology has also changed the paradigm of traffic analysis. [27] developed a hybrid model of conventional and CAV vehicles based on the Intelligent Driver Model (IDM), which showed an increase in road capacity of up to 15% at autonomous vehicle penetration by 40%. Similar results were found [28], who examined the interactions between autonomous vehicles and humans at intersections without signals. They found that the presence of autonomous vehicles does not necessarily increase capacity linearly as it depends on the adaptive behavior of the human driver around. In addition to vehicle models, traffic analysis also includes a perimeter control approach to regulate the number of vehicles entering dense urban areas. [29] developed a traffic control model based on Colored Petri Nets that takes into account the dynamics of queues at regional boundaries, proving effective in reducing delay times by up to 18% without the need for infrastructure expansion. This model utilizes the principle of predicting vehicle flow through MFD and predictive control algorithms to maintain a balance between the number of vehicles entering and exiting the area. Advances in sensor technology are also revolutionizing traffic data collection. [30] used Floating Car Data (FCD) data to build a real-time vehicle flow estimation model. They found that the use of a fundamental multiperiod diagram that considers the effects of hysteresis was able to increase the accuracy of traffic flow estimates by up to 7% compared to conventional models. This approach allows planners to monitor daily traffic dynamics with high precision, while supporting an early warning system against congestion. In the era of rapid urbanization and digitalization, traffic analysis is increasingly shifting towards data-driven and intelligent management approaches. [29] affirm the importance of macroscopic system modeling to avoid large computational loads on microanalyses, while probabilistic approaches such as those developed [31] provide a new framework for road capacity analysis that is adaptive to real-world conditions. Overall, traffic analysis is not only a technical instrument to measure network performance, but also a strategic tool to support sustainable transportation policies, improve safety, and optimize public resources in the development of transportation infrastructure.

In practice, traffic flow is not only affected by the number of vehicles, but also by other factors such as the geometric conditions of the road, weather, driver behavior, as well as side obstacles such as illegal parking or pedestrian activity. Therefore, traffic analysis is not only mathematical, but also requires an understanding of the social dimension and behavior of road users. To describe the operational quality of a road section from the user's perspective, the concept of the level of service (LOS) is used. The LOS scale is categorized from A to F: where LOS A describes free flow at high speed and minimal interaction between vehicles, LOS C–D represents stable current with little interference, LOS E indicates conditions close to maximum capacity, while LOS F indicates severe congestion with a near-stop current [32]. According to the research of [31], the relationship between road capacity and LOS is highly dependent on the efficiency of geometric design as well as traffic governance. They assert that increased capacity does not necessarily result in a significant increase in LOS, as the interaction of driver behavior and external constraints often limits the effectiveness of additional capacity. This is in line with the findings of [33] which highlight the importance of assessing the resilience and efficiency of road networks through indicators of functionality and service performance, especially in transport systems that are vulnerable to external disturbances such as disasters or environmental changes. In planning decision-making, LOS plays a role as a basic parameter of evaluation. If a road section shows an LOS D or lower, then planners usually consider interventions such as physical capacity building, construction of alternative routes, or the implementation of traffic management systems such as traffic signal coordination and one-way systems [34]. However, a number of recent studies have shown that increasing physical capacity is not a long-term solution because it can cause the phenomenon of induced demand — that is, an increase in vehicle volume due to increased comfort and speed after the repair project is completed [35]. This phenomenon induced demand has been studied in the context of rapid urbanization and the growth of private vehicles. The study of [36] developed a current allocation model based on the Frank-Wolfe (FW) algorithm to assess traffic redistribution due to changes in network capacity. The results show that the increase in road capacity without demand control only has a temporary effect on LOS improvement. Similarly, the research of [37] confirms the importance of an adaptive transportation policy-based approach that is not only oriented to physical infrastructure, but also considers aspects of people's travel behavior and demand patterns. On the other hand, LOS improvement can be achieved without increasing road capacity through operational optimization strategies and intelligent traffic management. This model includes the use of traffic sensors, adaptive signal control, as well as vehicle restriction policies based on time or region. The results of the research of [33] confirm that a network resilience-based control strategy can keep LOS in the C–D category even when there is a sudden spike in traffic demand. A similar approach was used [34] who assessed that infrastructure planning based on social cost and service degradation analysis provides more efficient results than a capacity building approach alone. The concept of road service level (LOS) serves as a balance indicator between technical efficiency, user comfort, and operational sustainability. In the context of modern transportation planning, LOS evaluations must take into account not only technical variables such as capacity and volume, but also external factors such as environmental conditions, driver behavior, and urban mobility policies. The application of these principles allows policymakers to formulate transportation strategies that are more adaptive, sustainable, and oriented towards the experience of road users.

Modern approaches in traffic analysis now make extensive use of digital technology and intelligent systems. One important breakthrough is the use of microscopic simulation models such as VISSIM and AIMSUN, which allow traffic planners to predict vehicle behavior in detail based on specific policy scenarios. These models can project the impact of road geometry changes, signal arrangements, or capacity additions on traffic flow and road service levels [38]. In their research, the use of the AIMSUN model showed that the implementation of policies such as the switch to electric vehicles and the implementation of Euro IV emission standards can significantly reduce carbon emissions in urban areas, although it is accompanied by new challenges related to battery energy consumption. Meanwhile, a Sumo-based simulation (Simulation of Urban Mobility) was used by [39] to examine the influence of the shape of urban blocks on traffic flow and air quality. The results show that urban spatial planning with rectangular blocks—such as in Barcelona—is able to generate more efficient traffic flow and lower emissions than triangular configurations. These findings reinforce the view that urban spatial planning and road design should be considered simultaneously in sustainable transportation management. Furthermore, the application of Intelligent Transportation Systems (ITS) has revolutionized the way traffic is managed in urban areas. ITS allows real-time monitoring of road conditions through CCTV cameras, vehicle sensors, and GPS data from road users. Systems such as LIDATS (Live Intersection Data Acquisition for Traffic Simulators) demonstrate the ability to capture and transmit traffic data directly from intersections, which are then used for adaptive signal setting and vehicle density analysis [40]. The development of traffic controllers based on machine learning is also an important focus in the latest research. A study [41] proposes an adaptive traffic control system that utilizes learning algorithms to improve the efficiency and sustainability of the road network. The results show that the application of learning controllers can optimize traffic signal settings while significantly lowering delay times and carbon emissions. In addition to focusing on technical aspects, modern traffic analysis also takes into account environmental and social impacts. Congestion not only hinders mobility, but also increases exhaust emissions and noise in urban areas. A study [42] shows that a combination of vehicle emission models and traffic simulators can accurately estimate the impact of air pollution on different types of roads. This approach helps policymakers assess the social impact of various transportation interventions. Furthermore, the concept of Complete Streets emerged, which emphasized that roads should be designed not only for motor vehicles, but also safe and comfortable for pedestrians, cyclists, and public transportation users. A cross-border study [43] highlights the importance of integrating autonomous and multimodal transportation systems in creating inclusive and efficient cities. In addition, the research of [44] reviewed traffic modeling techniques in the context of autonomous vehicles and interactions with conventional vehicles. They emphasize the importance of understanding mixed traffic dynamics to design safe and efficient future road networks. Modern traffic analytics has evolved from a conventional approach based on volume and capacity to data-driven, environmentally friendly, and inclusive systems. Through the integration of microscopic simulations, real-time data analytics, and human-oriented policies such as Complete Streets, future transportation systems are expected to be able to improve mobility efficiency while reducing ecological and social impacts.

In Indonesia, the main guide for traffic analysis and road service levels still refers to the Indonesian Road Capacity Manual (MKJI), which provides a methodology for calculating capacity and Level of Service (LOS) on various types of roads — from urban roads, inter cities, to toll roads. However, technological developments and the complexity of the movement demand an update to this conventional approach. Several recent studies show that big data-based models and the Internet of Things (IoT) are now able to provide real-time information about traffic flows with high accuracy, replacing static manual surveys [45]. The integration between vehicle GPS data and digital map applications is also an important instrument in modern traffic planning. This approach aligns with the global trend towards smart traffic management, where traffic data collection and analysis are done automatically to support evidence-based decision-making. These findings reinforce the view that capacity calculation systems should take into account road user behavior, vehicle characteristics, and typical traffic conditions of an area. In addition to the technical aspects, traffic analysis and service level assessment are also a reflection of how the community utilizes public space. As stated [37], the road space should not only be seen as a vehicle corridor, but as a space for social interaction that brings together economic, environmental, and safety interests. A holistic and humane approach to transportation analysis is also the focus of a study [46] which emphasizes that the success of transportation systems is determined by the balance between efficiency, comfort, and environmental sustainability. A similar concept was raised [47], who proposed an integrative framework based on human-centered mobility, in which highway design considers the emotional and social needs of users, not just the physical capacity of the road. In the context of sustainable development, traffic analysis now also takes into account environmental and social impacts, such as carbon emissions, noise levels, and comfort of non-motorized users. The study of [48] developed a sustainability-based traffic evaluation model that combines CO_2 emission and energy efficiency indicators to comprehensively assess road performance. The application of this cross-disciplinary approach is also in line with the views of [33] on the importance of strengthening the resilience of transportation networks to social and environmental disturbances, in order to continue to provide optimal services even in crisis conditions. Thus, modern traffic analysis in Indonesia needs to move beyond the traditional MKJI technical paradigm, towards a data-driven and human-based system, capable of balancing technical efficiency with social justice and ecological sustainability.

9.3. The Relationship Between Transportation Engineering and Agricultural Business Systems

Agriculture is a sector that relies heavily on an efficient transportation system. Without good road access and a connected distribution network, it is difficult for agricultural products to reach the market on time, thus reducing the selling value and welfare of farmers. The relationship between transportation techniques and agricultural business systems is very close because they form a chain of interdependent values. As revealed [45], strengthening logistics infrastructure and the application of digital technology has been shown to improve the efficiency of agricultural supply chains by up to 33% in a case study of the potato industry in Inner Mongolia. This shows that road connectivity and logistics digitalization play a direct role in increasing farmers' productivity and profits. Accessibility is a key element that determines the success of the agricultural business system. Farm roads, production roads, and inter-village networks function as vital routes for agricultural logistics. When roads are damaged or unpassable, supply chains are disrupted and cause significant post-harvest losses. The study of [49] found that in Sub-Saharan Africa, post-harvest losses on local vegetables reached more than 30% due to poor transport systems and distribution coordination. Thus, improving the quality of rural roads is not only an infrastructure project, but also a social and economic investment that has a direct impact on food security and farmers' welfare. In addition to physical access, transportation engineering also plays a role in optimizing agricultural logistics through the application of cold chain systems, route management, and shortest distance analysis. [50] research confirms that the application of post-harvest technologies such as High-Pressure Processing (HPP) and Modified Atmosphere Packaging (MAP) can significantly reduce agricultural yield losses when supported by an efficient refrigerated transportation system. With the integration of technology and transportation engineering, cold chains are able to maintain the quality of sensitive commodities such as vegetables, fruits, and livestock products until they arrive at the market. In the context of rural development, the improvement of road infrastructure has proven to be a major catalyst for increasing market access. [51] shows that the improvement of road networks and the provision of storage facilities significantly lower the cost of food logistics in Africa and Brazil, while stabilizing food prices and reducing hunger rates. A systematic study [52] in Supply Chain Analytics confirms that road connectivity, transportation availability, and logistics costs are the three main factors that determine food access, especially in remote areas. Good road access not only speeds up distribution, but also expands the market and improves the balance of prices between regions. Furthermore, the modernization of the agricultural transportation system is now directed at automation and digitalization. [53] found that the implementation of autonomous trucks in the agricultural supply chain in the United States was able to reduce transportation costs by up to 20% and improve delivery time efficiency, particularly in large agricultural areas such as North Dakota. The use of automated vehicles and V2V (Vehicle-to-Vehicle) communication systems have great potential to be applied in the agricultural sector to speed up logistics processes in developing countries. From an agricultural economics perspective, [54] emphasized that logistics efficiency and transportation availability have a direct effect on increasing farmers' incomes, especially in contract farming systems that require fast and timely delivery. The modern agricultural contract system requires the support of a planned transportation infrastructure in order to maintain the reliability of commodity delivery and maintain product quality. Good transportation connectivity not only increases economic efficiency, but also strengthens food security and the welfare of rural communities. The integration between transportation engineering science and agricultural supply chain management allows for the formation of a more resilient production system, adaptive to climate change, and oriented towards sustainable development. As the findings above show, transportation is not just a means of connecting regions, but the foundation for a productive, resilient, and equitable agricultural system.

The relationship between transportation techniques and agricultural business systems is gaining more attention in the study of modern rural development. Adequate road infrastructure has proven to be crucial in strengthening agricultural supply chains, improving farmers' welfare, and expanding access to production inputs such as fertilizers and seeds. [55] affirm that the development of electric mobility services in Ethiopia significantly improves the efficiency of the rural agricultural value chain through the provision of affordable and sustainable transportation. Research [56] shows that key performance indicators (KPIs) in sustainable rural mobility have a direct effect on the competitiveness of the local economy and the quality of life of agrarian communities. In the context of spatial planning, the use of geospatial technology and geographic information systems (GIS) is crucial in determining the priorities of rural road construction. [57] found that the integration of high-resolution satellite imagery and spatial analysis can identify inequities in transportation access in rural areas, thus aiding in more inclusive transportation planning. This is in line with the findings of [58], who used geospatial models to determine sustainable development zones based on accessibility and vital infrastructure, suggesting that strategic road access can accelerate the economic integration of remote areas. In addition to the technical aspect, transportation connectivity also has a social and environmental impact. The study of [59] highlights the importance of active mobility such as walking and cycling in rural areas as a form of inclusive mobility that supports environmental sustainability. Meanwhile, research [60] warns that road construction without good land use planning can lead to excessive conversion of agricultural land, threatening food security. On the other hand, the development of digital technology brings new potential in the integration between transportation and agricultural business systems. In addition, [61] highlight the opportunities for the deployment of small-sized autonomous vehicles in rural Australia to expand access to agricultural transport in an efficient and environmentally friendly manner. The synergy between transportation techniques, digital technology, and agricultural business systems not only serves to improve logistics efficiency, but also forms the foundation for resilient and sustainable rural development. Roads are not just physical infrastructure, but socio-economic catalysts that connect farmers to markets, innovation, and broader welfare opportunities.

9.4. Optimization of Goods Distribution in Kalimantan

Kalimantan is one of the largest islands in Indonesia that has a strategic role in the provision of natural resources and agricultural products. However, the complex geographical conditions — consisting of tropical forests, large rivers, and hilly areas — present great challenges to its transportation and logistics systems. The distribution of goods in Kalimantan is often hampered by limited road infrastructure, dependence on river modes, and high logistics costs between regions. This is in line with the findings of The Palgrave Handbook of Global Sustainability [62] which confirms that the tropics face logistical gaps due to distinctive ecological and spatial challenges. The transportation system in Kalimantan shows intermodal inequality, where dirt roads and laterites are still the main routes for the distribution of forest and plantation products. Edward Elgar's [63] study in the Handbook of Megacities and Megacity-Regions highlights that cross-modal connectivity—especially between land, river, and sea—is a decisive factor in improving distribution efficiency in large, low-density areas such as Borneo. For this reason, an integrative approach between river and land transportation is needed so that the logistics system becomes resilient to seasonal fluctuations and geographical conditions. A scientific approach based on route optimization and network analysis is a key solution in overcoming the challenges of goods distribution. The use of Geographic Information System (GIS) technology allows transportation planners to map the optimal route based on travel time and operational costs. A study published in ICONSTAS 2023 confirms that the integration of spatial data and logistics algorithms can reduce distribution costs by up to 25% in the hilly regions of Southeast Asia [64]. In the context of Kalimantan, methods such as the Vehicle Routing Problem (VRP) can be applied to the distribution of palm oil products from plantations to ports, taking into account weather factors and road conditions in real time. In addition to the technical approach, production area-based planning is key in distribution management in Kalimantan. The extractive industry-oriented regions of East and South Kalimantan require logistics lines with strong pavement and high capacity, while Central and West Kalimantan require a network of connecting roads between villages and small docks. Proceedings of the International Conference on Applied Science and Technology on Social Science [65] affirm the importance of a regional productivity-based logistics zoning approach in increasing the equitable distribution of economic development. In terms of public policy, the World Conference on Governance and Social Sciences [66] noted that the development of strategic infrastructure in inland areas such as Kalimantan directly contributes to the reduction of spatial inequality and national logistics costs. In practice, the government can use GIS-based spatial analysis to determine the priorities of production road and river port projects that best support the distribution of regional leading commodities. In addition, the Proceedings of the 5th Annual International Conference on Business and Public Administration [67] highlight the importance of synergies between the private and public sectors in funding the construction of logistics networks in resource-rich areas such as Kalimantan. The involvement of the plantation and mining industries in the construction of roads and ports can accelerate the efficiency of supply chains without completely burdening the public budget. The transportation-based regional economic approach is also affirmed in the Proceedings of the International Conference on Sustainable Innovation on Humanities, Education, and Social Sciences [68], which states that road infrastructure improvements in hinterland areas have a multiplier effect on market expansion and increased logistics investment. In the context of Kalimantan, improving access between districts and ports can reduce the cost of shipping plantation products by up to 18%. Finally, research results from the Proceedings of the 2nd International Conference on Democracy and Social Transformation [69] emphasize that the success of transportation infrastructure development in tropical regions is not only measured from economic aspects, but also from the ability to increase social inclusivity and environmental protection. Sustainable transportation-based approaches such as the use of local materials, adaptive drainage design, and community-based maintenance are the right solutions in regions like Kalimantan that are sensitive to ecological change. Optimizing the distribution of goods in Kalimantan requires a combination of technical, spatial, and socio-economic approaches. By utilizing GIS technology, integration of transportation modes, and data-driven policies, Kalimantan's logistics system can transform into an efficient, sustainable, and inclusive distribution network.

The main challenge in optimizing the distribution of goods in Kalimantan has to do with high logistics costs and lack of integration of multimodal systems. As highlighted in The Palgrave Handbook of Global Sustainability [62], logistics inefficiencies in regions with limited infrastructure increase carbon footprints and distribution costs, hence the need for a holistic approach that combines physical infrastructure and digital systems. The implementation of intelligent logistics management systems such as freight management systems and GPS-based tracking has been shown to strengthen supply chain efficiency in complex tropical regions, as described [70] in the AI Agency in Climate Emergency, which emphasizes the role of AI in optimizing green logistics in high-risk environmental risk areas. The development of the IKN in East Kalimantan is also an important catalyst in the development of regional logistics networks. [71] asserts that global and domestic supply chain integration requires synergy between land, sea, and air transportation to achieve large-scale efficiency. In the context of large projects such as IKN, a sustainability-oriented approach to construction project management, as outlined in the Handbook of Construction Project Management [72], becomes particularly relevant as it emphasizes cost efficiency, logistics risk management, and environmental sustainability. Furthermore, distribution optimization in Kalimantan needs to take advantage of a resilient urban and transit planning approach to geographical conditions. The book Urban and Transit Planning [73] explains the importance of coordination between transportation network planning and land use to support sustainable logistics systems in regions with complex topography. Meanwhile, the development of connectivity between regions must consider social and ecological impacts, as outlined in the Handbook of Megacities and Megacity-Regions [63], which shows that the growth of transport networks in new regions often puts pressure on ecosystems if not accompanied by adaptive spatial policies.

Table 9.1. Logical Framework for Optimizing the Distribution of Goods in Kalimantan

Objective Level	Description of Objectives / Activities	Performance Indicators (KPIs)	Verification Source / Data	Key Assumptions / Risks
Goal (Tujuan Akhir)	Improving logistics efficiency and economic connectivity in Kalimantan through a sustainable multimodal transportation system.	Reduction of regional logistics costs ≥ 10% in 5 years; An increase in interprovincial distribution volume ≥ 15%.	Data from Bappenas, Ministry of Transportation, national logistics report, academic studies (Kshetri, 2025).	National economic stability and cross-sectoral policy support.
Purpose (Tujuan Langsung)	Developing an efficient goods distribution system based on the integration of land, river, and sea with the support of digital technology.	Optimized number of multimodal routes; Improved reliability of delivery time (≥ 90% on time).	Logistics tracking systems, GPS data, regional transportation reports (Cheshmehzangi, 2025).	The availability of basic infrastructure and digital networks is adequate.
Outputs	1. GIS-based distribution optimization model and Vehicle Routing Problem (VRP).2. Improvement of the quality of production roads and small ports.3. Implementation of green logistics systems and digitalization of shipment management.	The availability of a digital logistics map of Kalimantan; The increase in the accessibility index of the area ≥ 20%.	IKN infrastructure project reports, surveys from the Ministry of PUPR and BPS.	Inter-agency collaboration and development funding are effective.
Activities	- Mapping of transportation networks with GIS.- Integration of transportation and economic data in national platforms.- Training of logistics operators in the use of digital systems.- Application of electric vehicles for short-distance distribution.	The number of trained human resources ≥ 200 people; 3 digital-based logistics systems are implemented.	Data on training and project implementation (Aerodrome Governance in Asia, 2025).	Availability of technology, electricity, and internet access in remote areas.
Inputs (Resources)	- Funding from the State Budget and private investment.- Support for GIS technology, AI, and supply chain management.- Collaboration between the government, universities, and the logistics sector.	The amount of investment per year; Number of active collaborative institutions.	Project financial statements and cooperation documents (Urban and Transit Planning, 2020).	Long-term commitment from all stakeholders.

Source: Author analysis, 2025

In terms of policy and governance, Aerodrome Governance in Asia [74] underscores the importance of the role of institutions and the private sector in ensuring the sustainability of regional logistics networks, including the management of logistics ports and airports in Southeast Asia. By combining AI technology, green supply chain management, and collaborative transportation governance, Kalimantan can become a model for the development of efficient and environmentally friendly tropical logistics. The optimization strategy for the distribution of goods in Kalimantan needs to emphasize three things: multimodal integration, logistics digitalization, and environmental sustainability. A data- and technology-based approach, as suggested [70] and [71], will strengthen regional connectivity while supporting Indonesia's vision as an archipelagic country with a smart and adaptive logistics system. Table 9.1 presents a logical framework for the development of the goods distribution system in Kalimantan that focuses on efficiency, sustainability, and logistics digitalization. The ultimate goal is to create a multimodal transportation system that can significantly reduce logistics costs and strengthen interprovincial connectivity. Through the purpose, the project is directed at the implementation of the integration of transportation modes with the support of intelligent technologies such as GIS and AI [70] [71],. Expected outputs include spatial data-based distribution optimization models, improvement of production road infrastructure, and the implementation of green logistics in accordance with global sustainability guidelines [62]. Core activities involve mapping the transportation network, digitizing supply chain management, and using electric vehicles to reduce carbon emissions. This logical framework illustrates the synergy between transportation techniques, public policy, and digital technology to realize a distribution system of goods in Kalimantan that is adaptive to geographical conditions and environmentally friendly.

Transportation engineering and highway construction have a fundamental role in creating an efficient, safe, and sustainable mobility system. From the discussion in this chapter, it can be concluded that transportation is not only a technical aspect in infrastructure development, but also an important instrument in supporting social welfare and economic growth. The basic principles of transportation engineering, such as movement efficiency, safety, accessibility, and environmental sustainability, are the foundation in designing a road network that is able to serve the needs of the community optimally. Traffic analysis and the level of service (Level of Service) are important tools in assessing the performance of the transportation system. Through this approach, engineers can identify congestion problems, road capacity, and socio-economic impacts of traffic policies. The results of the analysis are then used to formulate appropriate improvement strategies, both through physical capacity building, traffic flow management, and the application of intelligent transportation technology (Intelligent Transportation System). In addition, the linkage between transportation techniques and agricultural business systems shows that the existence of good road infrastructure is a catalyst for rural economic growth. Production roads and farm roads are not only means of transporting crops, but also bridges between the agricultural sector, industry, and the market. Thus, investment in rural transportation is an effective strategy to reduce economic disparities between regions and improve national food security. A case study of optimizing the distribution of goods in Kalimantan shows how the application of transportation engineering principles can answer geographical and logistical challenges in the archipelago. Through multimodal integration, logistics digitalization, and data-driven planning, distribution efficiency can be significantly improved even if infrastructure is still limited. An approach like this is a clear example that transportation development in Indonesia must be adaptive to local conditions, sustainability-oriented, and supportive of national connectivity. Transportation techniques and highway construction are the main pillars in realizing a mobility system that not only serves economic needs, but also improves the quality of life of the community. With the application of the right engineering science, supported by public policies that favor sustainable development, transportation can be the driving force of Indonesia's social and economic transformation towards a more connected, productive, and inclusive future.

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CHAPTER 10
AGRICULTURAL BUSINESS SYSTEMS AND SUPPORTING INFRASTRUCTURE

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Modern agriculture relies not only on natural factors such as soil, water, and climate, but also on the support of strong and integrated infrastructure. Infrastructure plays an important role in creating an efficient agricultural business system, from the production stage to the distribution of crops. Without adequate road, irrigation, energy, and transportation support, agricultural potential is difficult to develop optimally. Therefore, the development of agricultural infrastructure is an integral part of the national economic development strategy, especially in strengthening food security and farmers' welfare. In the context of Indonesia, the role of infrastructure is increasingly crucial given the vastness of the region and the variety of geographical characteristics between regions. The availability of national roads, logistics systems, water networks, and transportation technology determine the smooth flow of goods and services in the agricultural sector. In some areas, limited infrastructure is still a major obstacle for farmers to access markets, technology, and capital. In contrast, in areas where infrastructure has developed, the agricultural sector shows significant increases in productivity and added value. This chapter will discuss in depth how the agricultural business system is affected by the existence of supporting infrastructure. The discussion began with the role of infrastructure in strengthening the agricultural system, followed by an analysis of the relationship between national roads and the distribution of agricultural products. Then, a case study of the development of agribusiness corridors in Kalimantan will be presented as an example of the implementation of infrastructure integration on a regional scale. Finally, this chapter highlights the importance of integration between agricultural systems and transportation techniques to increase the productivity and sustainability of the agricultural sector in the future.

10.1. The Role of Infrastructure in Supporting the Agricultural Business System

The development of modern agriculture cannot be separated from the existence of adequate infrastructure. Infrastructure acts as the backbone that ensures all agricultural activities, from production to distribution, run smoothly. In many rural areas, limited infrastructure is often a major obstacle to farmers' productivity, as access to land, water, fertilizer, and markets becomes difficult. Damaged village roads, unmaintained irrigation networks, or limited crop storage facilities cause farming efficiency to decline and farmers' income is hampered. Recent research shows that investment in agricultural infrastructure has a direct impact on improving productivity and food security. In Somalia, increased domestic investment and agricultural infrastructure development have been shown to drive long-term growth in agricultural yields [1]. Similar results were found in sub-Saharan Africa, where rural infrastructure development has been shown to increase food security while reducing the negative impacts of climate change on agricultural yields [2]. Basic infrastructure such as roads, bridges, and irrigation are the main prerequisites in strengthening the agricultural business system. Roads and bridges facilitate the mobility of goods and labour, allowing farmers to sell their crops more quickly and reducing losses due to distribution delays. Meanwhile, the irrigation system plays a role in maintaining production stability by ensuring the availability of water throughout the season. A study by [3] shows that the development of rural energy infrastructure, especially at the electricity consumption stage, is the most significant factor in driving agricultural growth in Fujian, China. These findings confirm that stable energy availability is an important complement to irrigation and transportation systems. In addition to physical infrastructure, supporting components such as electrical energy and telecommunications are key in supporting modern agricultural systems. Electricity opens up opportunities for farmers to use mechanization, post-harvest processing, and cold storage, while access to telecommunications improves farmers' ability to access price, technology, and weather information. Research in Anhui, China, shows that the development of digital infrastructure significantly improves agricultural efficiency through supply chain optimization and reduced production costs [4]. The role of the government and the private sector has become strategic in providing and managing agricultural infrastructure. Investment in infrastructure should be directed not only to expand the physical network, but also to ensure the sustainability of its utilization. For example, agricultural roads require periodic maintenance, and irrigation systems require community-based management for equitable distribution. Studies in West Africa show that the success of agriculture depends not only on technology and natural resources, but also on the synergy between infrastructure, financing, and innovation [5]. Furthermore, the direction of global agricultural development is now moving towards integration between infrastructure and digital transformation. [6] affirm that the combination of technological innovation, digitalization, and supporting policies can form new quality productivity in the agricultural sector, accelerate modernization and increase the competitiveness of rural areas. Meanwhile, [7] show that the development of a sixth-generation (6G) communication network has the potential to revolutionize agricultural systems in Colombia through the implementation of Agriculture 5.0, which combines artificial intelligence, the Internet of

Things, and robotics. From these various studies, it can be concluded that the development of agricultural infrastructure is no longer just a physical project, but a comprehensive strategy that includes social, economic, technological, and environmental aspects. Infrastructure is the foundation for agriculture that is sustainable, adaptive to climate change, and able to compete in the global market. Through the right investments, cross-sector collaboration, and the integration of digital technology and clean energy, agricultural business systems can evolve in a more resilient, efficient, and inclusive direction.

Furthermore, infrastructure development should be seen as part of an integrated agribusiness system. Infrastructure not only serves to facilitate the flow of goods, but also forms a dynamic and productive rural economic ecosystem. With good infrastructure, new economic activities have sprung up around agricultural areas such as produce processing, local trade, and logistics services. This condition increases people's income and reduces the gap between villages and cities. Equitable infrastructure development also strengthens national food security because the distribution of agricultural products becomes more stable and efficient. The role of infrastructure in the agricultural business system is not just about physical development, but about building the foundation for resilient, inclusive, and sustainable agriculture. In Nepal, agribusiness investment linked to infrastructure development has been shown to accelerate the development of rural economies and increase the contribution of the agricultural sector to national GDP [8]. In a global context, the integration between infrastructure and agribusiness added value has been proven to be able to drive the transformation from subsistence agriculture to an efficient and competitive commercial production system [9]. Integration between infrastructure and agribusiness development also requires institutional and public policy support. A study in Nigeria confirms that collaboration between the public and private sectors in the provision of agricultural infrastructure and technology is a key factor in building a sustainable agribusiness system capable of facing the challenges of climate change and economic inequality [10]. The development of agribusiness infrastructure also has a significant impact on strengthening the capacity of rural workers. According to [11], the development of human resources and technology networks in the agricultural sector is a key strategy in increasing productivity while creating new jobs in rural areas. The development of modern agribusiness is now also directed at the integration of digital technology in the infrastructure system. [12] shows that inequality in agricultural business development can create social disparities in rural areas. Therefore, infrastructure development policies must pay attention to equality between regions so that economic benefits can be felt in an inclusive manner. This approach is in line with practice in Indonesia, where the implementation of agribusiness-based eco-friendly agriculture programs has been proven to increase productivity and strengthen the competitiveness of local agricultural areas [13].

Thus, strengthening agribusiness infrastructure is not only an investment in physical, but also in social, institutional, and knowledge capital. Infrastructure is a bridge between the potential of natural resources and the welfare of farmers, creating a connected, adaptive, and globally competitive agricultural system. In the context of national development, strengthening rural infrastructure should be placed as a top priority to build the foundation of inclusive, productive, and sustainable agriculture.

10.2. The Relationship Between National Roads and Distribution of Agricultural Products

The national road is the lifeblood that connects agricultural production centers with urban consumption markets. Its role is very vital in determining the efficiency of the distribution system of agricultural products. When the quality and connectivity of national roads are good, logistics costs decrease, delivery times are shorter, and the risk of damage to agricultural products due to long journeys can be reduced. On the contrary, damaged or poorly connected roads are often the main cause of high distribution costs, which ultimately reduces the competitiveness of agricultural products in national and international markets. Research in China shows that highway construction increases the profitability of agribusiness enterprises through transportation efficiency, expansion of market reach, and reduced operational costs [14]. The study confirms that better road access mainly has a positive impact on perishable products such as fruits, vegetables, and livestock products. These findings are in line with research results in Nigeria that highlight the importance of agricultural transportation in smoothing crop distribution and reducing post-harvest losses, especially in areas with limited access to infrastructure [15]. The quality of the road also has a big influence on farmers' access to the market. In Benue State, Nigeria, factors such as vehicle ownership, education level, and proximity to major roads have been shown to increase farmers' chances of selling their agricultural produce more widely and profitably [16]. A similar thing was found in a study in Peru, where improved road infrastructure in the Amazon forest region encouraged smallholder farmers to expand production activities and strengthen links with national supply chains [17]. National road connectivity not only has an economic, but also social and environmental impact. However, other research emphasizes that imbalances in infrastructure development can widen the gap between small and large farmers, as well as create new supply chain risks such as distribution delays or vulnerability to disasters [18]. In addition, national roads also serve as a catalyst for the formation of agricultural economic corridors. The main line connecting the production area with ports and logistics centers creates a new economic space that encourages the growth of the produce processing industry, storage facilities, and logistics services. Good infrastructure development has been proven to play a role in creating regional economic resilience, strengthening connectivity between regions, and reducing rural poverty levels through improving supply chain efficiency [19]. National roads not only facilitate the movement of goods, but also become the foundation for inclusive agriculture-based economic growth. Transportation infrastructure integrated with agribusiness systems allows farmers to access wider markets, shorten distribution chains, and improve welfare. In the context of national development, improving the quality and equitable distribution of national roads is a strategic step in strengthening food security, reducing logistics costs, and accelerating the transformation of rural economies towards independence and sustainability.

The social aspect is an inseparable part of the role of national roads in supporting the distribution of agricultural products. Good road infrastructure not only facilitates the flow of goods, but also labor mobility, access to public services, and economic interaction between villages and cities. Farmers can easily obtain means of production such as fertilizers and seeds and sell their crops on time. Adequate road access also supports sustainable agricultural activities because it facilitates the distribution of technology, counseling, and market information to the farming community. Thus, national roads are an important instrument in reducing spatial inequality and strengthening national agricultural competitiveness. Research in Cameroon shows that improving road infrastructure and basic facilities contributes significantly to reducing spatial inequality between regions and improving the well-being of rural communities [20]. Similar findings were also found in China, where rural infrastructure investments have been shown to increase farmers' incomes and strengthen economic linkages between agricultural and urban areas [21]. Meanwhile, a study in Africa [22] confirms that inclusive spatial planning and road networks are key factors in strengthening food security through increased public access to markets and resources. However, the construction of national roads also brings new challenges, especially related to spatial planning and the environment. Increased access without proper management can trigger the conversion of productive farmland to non-agricultural areas, ultimately threatening long-term food security. [23] warn that uncontrolled road expansion and urbanization can accelerate the process of urban sprawl, reduce productive green space, and increase ecological pressure in suburban areas. Therefore, national road development policies need to be aligned with regional spatial plans so that development continues to support the sustainability of natural resources. Other studies underscore the importance of integrating social and economic aspects in road construction. Research [24] shows that the existence of toll roads and national roads in Indonesia has a dual impact: increasing economic connectivity and job opportunities, but also has the potential to create new inequalities in unaffordable rural areas. From a socio-ecological perspective, [25] highlight that the construction of large-scale roads such as the

Semarang–Demak toll road has complex consequences: changes in settlement patterns, population mobility, and environmental degradation. Therefore, infrastructure planning needs to consider the balance between economic benefits, social sustainability, and ecological preservation. The relationship between national roads and the distribution of agricultural products is reciprocal and mutually reinforcing. National roads accelerate the flow of goods from producers to consumers, while increasing agricultural trade volumes encourage improvements in transportation infrastructure. In the context of globalization and climate change, synergy between road development policies, spatial planning, and food security strategies is key in creating an efficient, resilient, and highly competitive agricultural system.

10.3. Development of Agribusiness Corridors in Kalimantan

Kalimantan is known as one of the regions with the largest agribusiness potential in Indonesia. The large expanse of land, the availability of water resources, and the diversity of commodities such as oil palm, rubber, rice, and horticulture make this area strategic for the development of agribusiness corridors. However, for many years, this potential has not been optimally utilized due to limited infrastructure and connectivity between regions. Therefore, the concept of developing agribusiness corridors is present as an integrative approach that aims to strengthen the agricultural value chain through the provision of coordinated transportation, energy, and logistics infrastructure. International studies show that the development of economic corridors is an effective strategy to strengthen regional integration and accelerate agribusiness development. In South Africa, for example, the construction of the Lobito Corridor has been shown to strengthen agricultural export value chains and improve connectivity between production areas and regional markets [26]. The same concept can be applied in Kalimantan, where economic pathways connect plantation and horticultural production centers with export ports such as Pontianak and Sampit to reduce logistics costs and speed up distribution times. Furthermore, the agribusiness corridor approach is not only physically oriented, but also institutional. The development experience of the Laos-China Economic Corridor shows that the success of the agricultural corridor depends on coordination between local governments, the private sector, and research institutions, as well as fair and transparent land management [27]. In Kalimantan, similar collaborations can encourage the formation of an integrated agricultural economic zone where production, processing, and marketing activities are interconnected in a single value chain system. In addition, studies from East Africa highlight the importance of managing colonial infrastructure heritage in the formation of new corridors. In Mozambique, revitalized old infrastructure becomes part of a modern logistics system, connecting cities and the hinterland and opening up new economic opportunities along trade routes [28]. This is relevant for Kalimantan, which also has a long history of inland isolation and requires reconnection through effective cross-provincial transportation. The development of agribusiness corridors is also closely related to food security and social inclusivity. [29] emphasized that strengthening inclusive agricultural supply chains can create jobs and reduce poverty through the development of agricultural product storage, transportation, and distribution infrastructure. By building agribusiness logistics centers and warehouses at strategic points across Kalimantan, the government can strengthen connectivity between smallholders and global markets. In terms of innovation, digital integration and modern logistics are important elements. [30] highlight that the digitalization of agricultural supply chains and market networks can significantly improve the efficiency of agribusiness systems, especially through the application of information technology in value chain management. This is relevant to support the development of digital agribusiness terminals in Kalimantan that can connect farmers, industry players, and exporters in real-time. In addition, the policy aspect also plays a big role. [31] point out that the success of the national logistics system depends heavily on public-private coordination and improved regulatory efficiency in the transportation sector. In the context of Kalimantan, this can be implemented through local government partnerships with agribusiness companies to optimize agricultural product distribution channels. Finally, the dimensions of agricultural innovation and research play a strategic role in strengthening the competitiveness of agribusiness corridors. [32] emphasized that research-based innovation and disruptive technology can expand the added value of commodities and strengthen the competitiveness of rural areas. The development of bioenergy clusters around oil palm plantations in Kalimantan can be an example of the application of sustainable value-added research. The development of agribusiness corridors in Kalimantan should be seen as a multidimensional strategy — not only building roads and ports, but also building mutually reinforcing economic, social, and institutional networks. The integration of transportation, logistics, technology, and institutional innovation will make Kalimantan a center for strong and globally competitive agribusiness growth.

On the other hand, the development of agribusiness corridors in Kalimantan faces complex ecological and social challenges. Agricultural and plantation expansion often intersects with forest and peatland areas that are highly sensitive to environmental change. Experience in Africa shows that the transition to a green economy will only succeed when there is a balance between economic growth and ecosystem protection through integrated agroforestry and renewable energy policies [33]. In the context of Kalimantan, the application of similar principles can be carried out through the land zoning system and the conservation of buffer areas around agribusiness corridors. Infrastructure development in the agribusiness corridor must pay attention to the principle of sustainability by emphasizing the efficiency of land use and the implementation of environmentally friendly agricultural practices. Studies from Spain show that water and land infrastructure management based on community participation is able to strengthen the sustainability of regional development projects while maintaining their ecological and social value [34]. This approach can be adapted in Borneo to ensure that corridor development does not come at the expense of tropical forest ecosystems. A community-based approach is also important so that local communities become part of the development process, not just the recipients of impacts. A participatory study in Thailand shows that community-based mapping and local knowledge integration can identify ecosystem values and support community food security in economic corridor areas [35]. This principle is very relevant to be applied in the development of Kalimantan's agribusiness so as not to cause social inequality. In addition to the social aspect, ecological sustainability must also be strengthened through the application of green technology and renewable energy. Research from Thailand highlights the potential of community-scale biomass power plants as a solution for providing renewable energy based on agricultural waste that can support agribusiness activities in rural areas [36]. With a similar system, Kalimantan can develop an energy decentralization model to reduce dependence on fossil fuels in remote areas. Digital connectivity also plays an important role in supporting the transformation of agricultural systems. Cross-border studies confirm that the digitalization of agriculture through sensors, spatial maps, and online networks can improve supply chain efficiency and strengthen food security in rural areas [37]. By implementing digital technology and data-driven value chain monitoring systems, Kalimantan agribusinesses can increase access to the global market directly. It is also important to ensure that the construction of the corridor does not result in the loss of biodiversity. A study of ecological development scenarios in Africa shows that economic growth without ecological control will threaten natural resources and degrade people's well-being in the long run [38]. Therefore, the development of Kalimantan's agribusiness corridor needs to be accompanied by a long-term conservation plan based on environmental indicators. Furthermore, the implementation of green infrastructure in the agricultural sector has been proven to improve soil health, microbial diversity, and resilience to climate change, as evidenced [39]. The implementation of green infrastructure in Kalimantan can be carried out through agroforestry systems and natural vegetation-based land conservation along production corridors. Finally, an integrated approach that blends social, technological, and environmental dimensions is key to the success of sustainable agribusiness development. As concluded in the African Ecological Futures project, sustainable development requires synergy between governments, the private sector, research institutions, and communities in adaptive management of natural resources [38].

With this comprehensive approach, Kalimantan has the potential to become a model for developing an inclusive and climate-resilient green economy in Southeast Asia.

10.4. Integration with Transportation Engineering to Increase Productivity

The integration of modern transportation and agricultural systems is now the main foundation in creating an efficient and highly competitive supply chain. A study [40] shows that digitalization and dynamic logistics models can improve the efficiency of agricultural systems by optimizing resource allocation and transparency between supply chain actors. In the context of agriculture, an integrated transportation system accelerates the movement of inputs such as fertilizers and seeds, while ensuring that crops reach the market on time with maintained quality. This efficiency is even more important in the era of global supply chain uncertainty, where logistics flexibility is a determining factor for the sustainability of farming. Advanced transportation technology also allows for more adaptive multimodal systems. [41] developed a multimodal optimization model for the cold chain of food products, which is able to reduce costs, time, and carbon emissions in agricultural product transportation systems. A similar approach is applied in the context of export agribusiness in Ukraine, where [42] show that agricultural containerization improves the efficiency and logistics resilience of agricultural products exports. The efficiency of agricultural transportation is also closely related to infrastructure management and intermodal connectivity. [43] emphasized the importance of integration between the public and private sectors in overcoming national logistics barriers, especially for countries with limited transportation infrastructure. On the other hand, [44] highlight the importance of integrating biomass and agricultural value chains to support sustainable energy, asserting that collaboration across transportation modes is able to reduce costs and improve the efficiency of resource distribution. In addition to physical logistics, the digitalization aspect is the key to the transformation of agricultural transportation. [45] show that the application of information technology and digital supply chain management improves global economic security and strengthens the competitive position of the agribusiness sector. In the context of cold chains, [46] emphasized the role of smart logistics in strengthening the e-commerce supply chain of fresh agricultural products, especially post-pandemic. The development of green transportation corridors is also relevant for sustainable agricultural systems. The study of [47] in Brazil proposes a Network Equilibrium Model approach to evaluate the efficiency of multimodal agricultural logistics corridors, which can be applied in the context of agribusiness infrastructure development in Indonesia. The overall study confirms that the integration of transportation techniques with agricultural business systems not only improves logistics efficiency, but also strengthens national competitiveness and food security through smart, green, and sustainable connectivity.

The efficient use of transportation is now one of the main factors in reducing carbon emissions and encouraging sustainable agriculture. Logistics efficiency not only saves costs, but also accelerates the transition to low-carbon farming systems. A study [48] confirms that the improvement of green logistics efficiency in agricultural products is strongly influenced by environmentally friendly technological innovations, attention to carbon governance, and the application of circular economy principles in the transportation sector. This integration shows how careful supply chain management can reduce greenhouse gas emissions without reducing economic efficiency. In the context of agricultural cold chains, the use of environmentally friendly fueled vehicles and digital-based logistics systems has been proven to be able to significantly reduce carbon footprints. [49] identified that cold transportation efficiency, implementation of carbon-neutral plans, and optimal arrangement of logistics nodes are three key factors in the transformation of agricultural supply chains towards low-carbon systems. The implementation of a similar system in Indonesia can strengthen the competitiveness of horticultural and fishery products in the face of strict export demands related to environmental standards. The importance of low-carbon policies is also revealed [50] who show that the integration of carbon tax policies and green incentives can balance rural economic growth with a reduction in transportation emissions. This indicates that the development of agricultural transportation systems needs to be accompanied by regulations that support the transition to a green economy. A similar approach can be adapted for Indonesia's agrarian regions through incentive policies for biofuel-based transportation and the use of renewable energy in the logistics sector. Digital technology and blockchain also play a role in reducing agricultural transportation emissions. [51] show that the application of blockchain-based supply chain technology can increase transparency, reduce waste, and encourage energy efficiency in the distribution of fresh produce. With this system, every stage of distribution can be monitored to ensure that emissions and energy consumption are at optimal limits. In addition, research [52] confirms the importance of carbon trading policies in driving the transformation of agricultural logistics at the regional level. Through simulations in China's cold logistics sector, they found that the implementation of carbon trading mechanisms can reduce energy consumption by up to 15% without sacrificing distribution efficiency. This approach is in line with Indonesia's efforts to implement carbon trading in the energy and agricultural transportation sectors.

Table 10.1. Strengthening the Agricultural Business System and Supporting Infrastructure in Indonesia

Hierarchy of Objectives	Description / Statement of Purpose	Objectively Verifiable Indicators	Means of Verification	Key Risks
Goal	Realizing a resilient, efficient, and sustainable national agricultural system through the integration of physical infrastructure and green transportation.	- Increase the efficiency of the national agricultural supply chain ≥20% by 2030.- Reduce carbon emissions of the agricultural logistics sector ≥15%.	- Data from the Ministry of Agriculture, Transportation, and Environment.- National carbon emission report (NDC Indonesia).	- The government's policy commitment to the green economy is consistent.- National social and political stability is maintained.
Purpose	Optimizing agricultural connectivity and transportation through sustainability-oriented infrastructure development and digital technology.	- 70% of production center areas are connected to a quality national road network.- Adoption of digital logistics technology by ≥50% of agricultural cooperatives or MSMEs.	- Agricultural infrastructure connectivity survey (Bappenas, 2027–2030).- Data on the use of digital logistics applications (Ministry of Communication and Information).	- Availability of long-term funding for agricultural infrastructure projects.- Adequate regional human resource capacity for technology adoption.
Outputs	1. Improvement of the quality and reach of road, irrigation, and rural logistics infrastructure.2. Implementation of green and energy-efficient transportation systems.3. Establishment of region-based agribusiness corridors in Kalimantan and other strategic areas.4. Adoption of digital supply chain technology and carbon monitoring systems.	- 2,000 km of farmland roads are connected to national lines.- 10 low-carbon agricultural cold chain projects are operating.- 3 fully functional agribusiness corridors (Kalimantan, Sulawesi, Sumatra).- Supply chain digital platforms are implemented in ≥5 provinces.	- Project report of the Ministry of PUPR, Agriculture, and Transportation.- Monitoring report of Bappenas and research institutions.	- Coordination between ministries is effective.- Public-private investment support is increasing.
Activities	- Construction and rehabilitation of farming roads and micro irrigation.- Implementation *of green logistics* based on renewable energy (biofuel, EV, solar hybrid).- Construction of agribusiness ports and regional logistics terminals.- Development of IoT and blockchain-based supply chain data systems .- Green logistics management training for local agribusiness actors.- Ecoregion-based environmental and spatial studies.	- Number of physical projects completed on time.- The level of community participation in training (≥70%).- The amount of logistics data integrated in the national system.	- Annual project reports and development audits.- IoT monitoring data and digital applications.- Evaluation of local community participation.	- Climatic and geographical conditions do not hinder development.- Energy and digital infrastructure support implementation.

Transportation efficiency can also be improved through the layout of production and distribution facilities that consider the balance between cost and emissions. A study [53] in the United States shows that the optimization of ethanol production sites and factories in corn farming areas can significantly reduce carbon emissions through efficient spacing and distribution lines. This principle can be applied to agribusiness infrastructure planning in Kalimantan or Sulawesi to shorten the distribution chain of agricultural products. Globally, [54] show that consumer awareness of low-carbon supply chains has also strengthened the demand for environmentally friendly agricultural products on e-commerce platforms. This signifies that the transformation of agricultural transportation systems not only impacts efficiency, but also shapes sustainable consumption behavior. Finally, an adaptive and environmentally friendly transportation system is the main foundation for the resilient agriculture of the future.

The integration of green transportation techniques, digital innovation, and carbon policies will strengthen Indonesia's agricultural competitiveness in the global market. Through cross-sector collaboration and smart technology support, agricultural transportation serves not only as a logistics driver, but also as an accelerator of productivity and sustainability. Logical framework (Table 10.1.) Departing from the assumption that agricultural infrastructure (roads, irrigation, energy, logistics) and green transportation techniques are key factors in increasing the productivity and efficiency of the national agricultural system. Success is achieved through policy synergy between sectors, integration of digital technologies, and local community participation. International studies such as [48] and [50] show that the integration of green logistics in agricultural systems increases efficiency by up to 25% and lowers carbon emissions by 18%, when supported by digital incentive and innovation policies. With this approach, Indonesia's agricultural system is expected to transform into a sustainable, highly competitive, and export-oriented agribusiness ecosystem, without sacrificing social and ecological balance.

The development of a resilient agricultural business system cannot be separated from the role of solid and integrated infrastructure. From national roads to irrigation networks, from logistics systems to modern transportation techniques, all elements of infrastructure contribute to improving efficiency, productivity, and farmers' welfare. Infrastructure is not only a physical means that facilitates agricultural activities, but also a symbol of the connection between regions, people, and new economic opportunities in the countryside. Through case studies such as the development of agribusiness corridors in Kalimantan, it can be seen that infrastructure integration is able to change agricultural production patterns to be more planned, connected, and high added value. However, the success of this development still depends on good governance, collaboration between sectors, and commitment to the principles of environmental sustainability. Infrastructure that is built without considering social and ecological aspects can actually cause inequality and degradation of natural resources. Therefore, the development of agricultural infrastructure must be placed as a long-term strategic investment. The government, the private sector, and the community need to work together to design a system that not only facilitates the flow of goods, but also strengthens the capacity of farmers as the main actors in the agribusiness value chain. With inclusive, efficient, and sustainable infrastructure, Indonesia's agricultural sector will be able to develop into a major pillar of national development that is independent, modern, and globally competitive.

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CHAPTER 11

ENVIRONMENTAL TECHNOLOGY IN SUSTAINABLE DEVELOPMENT

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Sustainable development is a new paradigm in resource management that emphasizes a balance between economic growth, social justice, and environmental sustainability. In this context, technology plays an important role as a tool to bridge development needs with the earth's ecological boundaries. Technological advances, if directed appropriately, can be a solution to various environmental problems that arise due to uncontrolled industrialization and urbanization. Therefore, environmental technology is emerging as a strategic field that integrates science, engineering, and policy principles to create an efficient, adaptive and nature-friendly development system. Environmental technology can be understood as the application of technical innovation that aims to reduce the negative impact of human activities on the environment and improve the quality of the ecosystem as a whole. The application of this technology covers various sectors — from renewable energy, waste management, water conservation, to green infrastructure development. The approach to environmental technology focuses not only on damage mitigation, but also on preventive and restorative efforts that foster a harmonious relationship between humans and their environment. Thus, environmental technology is not just a technical tool, but also part of a comprehensive and long-term oriented development strategy.

In the context of infrastructure development, the role of environmental technology is very central. Infrastructure is the backbone of national development, but construction activities often have considerable environmental impacts such as carbon emissions, pollution, and land degradation. Therefore, the application of green technology in infrastructure projects, for example through energy efficiency, waste treatment systems, and the use of environmentally friendly materials, is an important step in reducing ecological pressure. This approach not only improves the quality of the environment, but also improves resource efficiency and the resilience of infrastructure to climate change. Furthermore, the field of road engineering has also undergone a major transformation through the use of environmentally friendly materials. This concept involves innovation in the use of recycled materials, industrial waste, and renewable natural materials. The use of green materials not only serves to reduce costs and environmental impacts, but also improves the quality and technical life of road pavement. With the development of research and technology, sustainable road engineering is becoming an important part of the global effort to create an efficient, low-emission and environmentally sound transportation system. One concrete example of the application of environmental technology on a national scale can be seen in the development of the Nusantara Capital City (IKN) in East Kalimantan. The project is designed as a living laboratory for the application of the concept of green and smart cities. Through the use of renewable energy, electric transportation, closed water management systems, and digital infrastructure based on environmental data, the IKN is expected to become a model for sustainable future urban development. The integration between green technology and smart governance makes the IKN a tangible proof that technological progress can run in harmony with environmental conservation. However, behind this great potential, the application of environmental technology cannot be separated from various challenges. High investment costs, limited human resources, lack of technical standards, and low public awareness are the main obstacles in the implementation process. In addition, the success of technology implementation is also greatly influenced by institutional and regulatory factors that support green innovation. However, opportunities for environmental technology development continue to increase in line with global commitments to reducing carbon emissions, digital technology advancements, and public awareness of the importance of sustainability. Chapter 11 will thoroughly discuss the role and application of environmental technology in the context of sustainable development. The discussion began with the application of environmental technology in infrastructure projects, followed by the use of environmentally friendly materials in road engineering, then a case study of the use of green technology in IKN, and finally an analysis of the challenges and opportunities for its implementation in the future. Through this study, it is hoped that readers will gain a comprehensive understanding of how technological innovation can be a major driving force in realizing sustainable, adaptive, and equitable development for current and future generations.

11.1. Application of Environmental Technology in Infrastructure Projects

Infrastructure development is one of the main pillars in supporting economic growth and community welfare. However, these activities often have a significant impact on the environment, both in the form of greenhouse gas emissions, water and soil pollution, and degradation of natural ecosystems. Therefore, the application of environmental technology is very important to ensure that infrastructure development can go hand in hand with the principles of sustainability. Environmental technology here includes a variety of innovations designed to minimize negative impacts on the environment, such as clean energy use, waste management systems, resource efficiency, and planning based on Life Cycle Assessment (LCA). In the context of modern infrastructure, the integration between energy efficiency and sustainability has become a key focus of global research. [125] show that the application of sustainable geotechnical techniques, such as bio-based soil stabilization and the use of local materials, can reduce the carbon footprint while increasing the resilience of infrastructure to climate change. This approach reinforces the concept that environmental engineering not only aims to reduce negative impacts, but also plays a role in creating adaptive and resilient infrastructure. In addition, the development of renewable energy systems in infrastructure projects is also showing promising results. [126] through the Lifecycle Analysis of Marine Renewable Energy Infrastructures study found that the application of marine energy technology (MRE) significantly reduces carbon emissions throughout the project life cycle, while supporting energy efficiency in coastal areas. In the terrestrial context, [127] emphasize the importance of utilizing solar, wind, and biomass energy combined with artificial intelligence for the optimization of energy systems in various sectors, including construction and public infrastructure. One prominent form of application of environmental technology is the use of renewable energy in infrastructure projects. Solar-based public street lighting, water pumping systems with wind energy, and the application of solar panels in government buildings are concrete examples of transformation toward green infrastructure. [128] research confirms that the combination of technological innovation and modern architectural project management can balance cost efficiency, sustainability, and productivity in global urban infrastructure projects. In addition, the implementation of energy efficiency systems and smart automation has helped improve energy performance while reducing long-term operational costs. [129] developed a machine learning lifecycle management framework that can improve the efficiency of energy distribution networks and reduce pollution through predictive maintenance and real-time resource management. The presence of AI-based technologies and data science also strengthens the approach to sustainability. According to recent research, the application of machine learning algorithms and predictive systems in energy design and management can increase network resilience and support overall resource efficiency [129]. This approach shows how digital advances not only play a role in economic efficiency, but also as a key driver in climate change mitigation efforts. Furthermore, material innovation and structural design help support the transition to sustainable infrastructure. [125] and [126] emphasized the importance of using hybrid materials and bio-based composites in construction that extend the life of infrastructure while reducing energy consumption at the operational stage. Meanwhile, the integration of circular economy principles and smart monitoring systems in smart infrastructure is a new focus to ensure that modern development is not only efficient, but also ecologically and socially sustainable. The application of environmental technology in modern infrastructure projects reflects a blend of technical innovation, energy efficiency, and ecological awareness. The lifecycle-based approach, supported by innovative digital and material technologies, provides a new direction for more adaptive and environmentally responsible development.

In the context of water and waste management, environmental technology plays an important role in maintaining the balance of the ecosystem around construction projects. The application of water recycling technology allows wastewater from the construction process to be reused after going through the filtration and purification stage. This approach is particularly relevant in areas with limited water availability. According to Springer Nature's "Sustainable Waste Management, Challenges and Visions" [130], the implementation of circular systems in liquid waste management can save up to 40% of clean water consumption through the integration of filtration systems and natural microbial bioprocesses. On the other hand, bioremediation technology is a strategic step in restoring the quality of the soil and water environment polluted by development activities. The book Environmental Science and Engineering [131] highlights the use of bacteria and fungi as effective bioremediation agents to lower the levels of heavy metals and hydrocarbons in soils around large industrial and infrastructure areas. This innovation in biotechnology is one of the efficient and environmentally friendly approaches in modern construction waste management. In addition to water management, digital sensor-based dust and air pollution control technology is now an important part of the project's environmental monitoring system. According to the Circular Economy and Green Transition in the Global South [132], Internet of Things (IoT)-based sensor systems are capable of detecting pollutant particles in real-time, providing dynamic data for decision-making to reduce emissions in construction areas. This marks a shift toward a data-driven approach in the management of infrastructure project emissions. Another aspect that is no less important is the management of construction materials. Digital technologies such as Building Information Modeling (BIM) have changed the way project planning, design, and control are carried out. With BIM, material usage can be optimized, reduce waste, and significantly reduce construction waste. Proceedings of the 11th International Conference of Ar.Tec. [133] affirms that the implementation of digital twin-based BIM allows simulation of the project's environmental impact before construction begins, so that the design can be adjusted to achieve maximum resource efficiency. Furthermore, the 5D Digital Environmental Impact Assessment (EIA) concept proposed [134] demonstrates the integration of BIM with real-time monitoring and cumulative evaluation of environmental impacts, which supports an evidence-based approach to sustainable development. Although it originated in the journal Sustainability, its methodological approach is widely adopted by major publishers such as Elsevier and Springer within the framework of green infrastructure evaluation. In modular and prefabricated technologies, this trend has proven to be able to reduce ecological impact as well as construction time. The 4th International

Conference "Coordinating Engineering for Sustainability and Resilience" [135] affirms that modular construction reduces the volume of construction waste by up to 30% and optimizes energy efficiency at the project site. This approach also improves work safety and allows for the reuse of building components in the next construction cycle. In addition to structural efficiency, Structures and Architecture: A Viable Urban Perspective? [136] underline that modular-based design with the support of digital technology is capable of creating structures that are not only efficient, but also adaptable to urban social and ecological contexts. This integration between engineering and architectural approaches reinforces the role of technology as a catalyst in the development of sustainable cities. Finally, in the context of waste and material resource management, Circular Economy and Green Transition in the Global South [132] emphasizes the need to apply circular economy principles throughout the construction supply chain, where building materials, water, and energy are treated as constantly rotating resources, not disposed of. The integration of environmental technology in the management of water, waste, air, and construction materials forms a unified system that strengthens each other. Through the use of digital technologies such as BIM, smart sensor systems, and modularization, infrastructure development can be directed toward high efficiency with minimal ecological impact. This approach marks a paradigm shift from conventional construction to smart and sustainable infrastructure systems, which are an important foundation for future development.

In addition to the direct application of technology, digital technology-based supervision is an important component of sustainable infrastructure projects. The use of IoT sensors to monitor air quality, noise levels, and soil stability has been proven to be able to provide real-time environmental data that can be acted upon immediately. A study [137] shows that the application of Industrial Internet of Things (IIoT) systems in construction can reduce energy consumption by up to 20% through automatic optimization of ventilation and lighting systems based on environmental data. A similar approach is also described [138] who emphasize the use of digital twins to monitor infrastructure performance and detect changes in environmental conditions predictively, reinforcing the concept of triple bottom line in sustainable development. By combining IoT and digital twins, construction projects can be more adaptive to environmental dynamics without sacrificing technical efficiency. The concept of smart city and smart infrastructure is the most real model of the application of this technology-based supervision. A study [139] in the Journal of Urban Research explains that the city of Playas, Ecuador, successfully integrates IoT, big data, and cloud computing technologies to simultaneously control air pollution and energy efficiency in the framework of transformation toward a sustainable city. Meanwhile, research [140] confirms that the application of IoT in the urban sector can increase energy efficiency by up to 25% while reducing carbon emissions with automatic optimization in transportation and utility systems. The application of digital environmental monitoring technology is not only oriented to ecological aspects, but also has a wide social and economic impact. According to a study [137], the integration of Industry 4.0 in infrastructure management not only reduces waste and emissions, but also opens up new job opportunities in the field of clean technology and sustainable industrial automation. From the socio-economic side, the implementation of a technology-based green economy also has a significant impact on strengthening the capacity of local human resources. A study [138] confirms that the integration of digital systems in the circular economy is driving the growth of new jobs in the fields of environmental data analytics, green building design, and sensor-based resource management. Although the study was exploratory, the findings showed a positive correlation between the adoption of clean technologies and increased local economic competitiveness. This approach emphasizes the integration of social, economic, and technological dimensions in the architecture of future sustainability. Finally, the book Digital Twin-driven Circular Economy [138] confirms that the use of intelligent surveillance technology connected to energy and materials management systems can reduce long-term operational costs by up to 35%, while extending the life of infrastructure with data-driven predictive maintenance strategies.

Although the application of environmental technology provides various benefits, there are still a number of challenges that need to be overcome. High initial cost barriers, limited technical knowledge in the field, and resistance to changes in work habits are factors that often hinder implementation. Therefore, government policy support is needed that encourages green innovation through fiscal incentives, clear regulations, and collaboration between the public, private, and academic sectors. In this context, the role of research institutions and universities is crucial in developing technologies that suit local conditions and community needs. The application of environmental technology in infrastructure projects is not only an option, but a necessity in facing the challenges of climate change and natural resource degradation. Through the application of the right technology, infrastructure projects can be the driving force of sustainable development that pays attention to the balance between economic, social, and environmental aspects. The transformation toward green infrastructure requires collective commitment, sustainable innovation, and cross-sectoral integration so that the benefits can be felt comprehensively for current and future generations.

11.2. Use of Eco-Friendly Materials in Road Engineering

Road engineering is one of the fields of civil engineering that has a major impact on the environment, ranging from the exploitation of raw materials, energy consumption in the production process, to the carbon emissions generated during construction and operation. Therefore, the use of environmentally friendly materials in road construction is an important strategy in realizing sustainable transportation infrastructure. This approach not only lowers the environmental impact, but also improves resource efficiency, extends road life, and reduces long-term maintenance costs. One of the most prominent innovations in this regard is the use of Reclaimed Asphalt Pavement (RAP), which is asphalt recycled from old roads that is reprocessed to be used as a new mixed material. According to [141], the use of RAP can reduce carbon emissions by up to 12% and energy consumption by up to 15% compared to conventional asphalt. In addition to saving natural resources, this technology supports the transition to a circular economy by significantly reducing the production of construction waste. Research [142] reinforces these findings, showing that the integration of RAP in the economic cycle of road construction can improve the structural resilience of roads while lowering the overall carbon footprint. The study also highlights the effectiveness of bio-based rejuvenator additives that are able to restore the properties of old asphalt, making this recycling not only efficient but also high-performance. In addition to RAP, Warm Mix Asphalt (WMA) technology has become a major focus in sustainable road research. [143] stated that WMA production at lower temperatures than Hot Mix Asphalt (HMA) can reduce carbon dioxide emissions by up to 30% and energy consumption by up to 40% without degrading the structural quality of pavement. Similar results were demonstrated [144], who found that the application of WMA lowered exhaust gases and fine particulate matter by up to 36%, making it a practical solution for the reduction of road industrial pollution. From an economic perspective, the use of recycled materials has also proven to be more efficient. [145] through the Life Cycle Cost Assessment (LCCA) showed that the combination of RAP and WMA saves construction costs of up to 25% over the life of the project compared to conventional materials, mainly due to energy efficiency and longer structure life. A study [141] in Developments in the Built Environment used the LCA approach to measure the impact of carbon emissions from modified RAP mixtures. The results show that at the production stage, emissions can be reduced by 18–36%, while total energy use is reduced by 15–87% with optimization of mixing and fuel temperatures. On the other hand, research [146] confirms that in hot climates such as the Middle East, the combination of RAP and WMA technologies can reduce the burden of carbon emissions over the 30-year project life by 28% compared to conventional approaches, while strengthening the quality of urban roads. [143] also highlight the great potential of the use of industrial waste-based materials and bio-based composites in road engineering, such as glass powder, fly ash, and recycled rubber, which can improve resistance to deformation and extend service life by up to 20%. This approach not only reduces emissions, but also expands sustainable local material options for the future of transportation infrastructure. The results show that the combination of RAP, WMA, and environmentally friendly additives provides dual benefits—both economically and ecologically. In addition to reducing the need for new raw materials, this technology strengthens road technical performance, reduces carbon emissions, and supports the transformation toward a low-carbon infrastructure development system.

In addition to RAP, the use of industrial waste as a substitute material in road engineering is now becoming an increasingly popular practice in various countries. Fly ash, steel slag, and cement kiln dust have been used as a substitute for some fine aggregates or binders in pavement construction. This approach is in line with the principles of the circular economy, where industrial waste is converted into valuable construction resources. According to the Handbook of Climate Change Mitigation and Adaptation [147], the use of mineral-based waste such as fly ash can reduce carbon emissions by up to 20% compared to conventional materials, while increasing energy efficiency in the production of building materials. In material performance, a comprehensive study extracted [148] shows that the incorporation of fly ash and steel slag not only reduces the volume of industrial waste ending up in landfills, but also increases the compressive strength and durability of pavement against heavy traffic loads, making it a technically competitive sustainable solution. In addition, the development of innovative materials has also led to the use of geopolymer materials as a substitute for Portland cement. Based on the Dictionary of Concrete Technology [148], geopolymer materials formed through reactions between aluminosilicates and alkaline activators have 60–80% lower carbon emissions than conventional cement, with better chemical and thermal resistance. The use of this material is particularly relevant for construction in tropical regions due to its ability to resist weathering and sulfate reactions. In the context of natural materials, bio-based additives such as lignin, tannins, and natural resins are also beginning to be developed as partial replacements for asphalt binders. According to Bio-Based Building Materials [149], bio-based bindings have strong adhesive properties and are able to increase the flexibility of asphalt mixtures at extreme temperatures, thereby reducing the risk of cracking and deformation. The use of local resources such as lignocellulose and plant extracts also strengthens the aspect of material independence and reduces the carbon footprint of material transportation. On the other hand, permeable pavement technology is now widely applied as an innovation based on ecological functions. This system allows rainwater to seep into the soil, reduces surface runoff, and supports groundwater replenishment. A study from Bio-Based Building Materials [150] noted that the use of porous concrete and open-structured aggregates can reduce standing water by up to 70% in dense urban areas. Thus, this system plays an important role in urban flood mitigation and groundwater quality improvement, in line with the vision of developing eco-cities and smart cities. The integration of all these technologies—whether based on industrial waste, geopolymers, biomaterials, or permeable systems—shows that material innovation can be the backbone of green road engineering. This approach not only reduces carbon emissions and natural resource consumption, but also opens up great opportunities for the development of sustainable and globally competitive local materials.

In addition to the main materials, the use of additives from sustainable sources such as natural fibers (coconut, bamboo, or kenaf fibers) has also been shown to be effective in improving the structural resilience of road pavement. Natural fibers have good mechanical properties and are easy to decompose in nature, making them more environmentally friendly than synthetic fibers. This innovation provides a great opportunity for tropical regions such as Indonesia, which are rich in biological resources, to develop pavement technologies that are more sustainable and based on local potential. The application of green materials in road engineering is not only limited to the material aspect, but also includes energy-efficient production and construction processes. The use of cold mix asphalt technology, for example, allows the construction process without high heating, so that energy consumption and greenhouse gas emissions can be suppressed. Likewise, road component prefabrication technology reduces construction time and environmental disturbances at the project site. However, the application of environmentally friendly materials also faces a number of challenges. The main challenges lie in the consistent availability of raw materials, the lack of uniform technical standards, and the relatively high initial cost compared to conventional materials. In addition, most contractors and implementers still tend to choose traditional materials because they have been tested in the long term. Therefore, there is a need for regulatory and policy support from the government that encourages the adoption of green materials through incentives, certification of environmentally friendly products, and the integration of sustainability aspects in design standards and infrastructure procurement. In the future, the global trend of road construction will increasingly lead to the concept of green and low-carbon infrastructure. The development of recycling-based material technology, biomaterial innovation, and the integration of digital systems for road life cycle monitoring will be important pillars in future road engineering. By making wise use of the potential of local technology and resources, road engineering not only serves as a means of transportation, but also as an integral part of a sustainable development ecosystem that supports human well-being and environmental sustainability.

11.3. Utilization of Green Technology in IKN

The development of the IKN in East Kalimantan is designed as a national project that not only serves as the center of the new government, but also as a symbol of the transformation toward a green and sustainable civilization in Indonesia. The concept of IKN development carries the principle of smart, green, sustainable, and resilient city, which means that every element of development must integrate technological aspects and environmental sustainability. In this context, the use of green technology is the main foundation to ensure that the development of the capital city does not repeat the mistakes of conventional urbanization that often ignores the ecological balance. One of the most tangible applications of green technology in the IKN is the use of renewable energy as the main source of electricity supply. The government targets that most of the energy needs in the IKN will be met through clean energy sources, such as solar, wind, and biomass. The construction of a solar farm in the North Penajam Paser area is a strategic step in supporting the energy transition. Solar panels are installed in various public facilities, government buildings, and residential areas to minimize dependence on fossil fuels. In addition, the use of smart grid technology is expected to optimize energy distribution and use efficiently and allow the dynamic integration of renewable energy sources as needed.

Various international studies support the importance of integrating green technology and renewable energy in sustainable city development such as IKN. The development of smart energy systems through smart grids has been proven to be able to improve energy distribution efficiency and support the dynamic integration of various clean energy sources such as solar, wind, and biomass. A study [151] confirms that smart cities based on renewable energy require energy planning that is aligned with urban planning to achieve maximum efficiency and energy security. Meanwhile, [151] show that a combination of photovoltaic systems, wind, and biomass in urban and rural areas can significantly reduce carbon emissions and improve local energy security. Other research highlights the role of city policies in driving the energy transition, where the implementation of renewable energy strategies in the European region has been proven to reduce emissions and increase urban preparedness to face the energy crisis [152]. In addition, [153] explain that the application of solar panels and wind turbines in public buildings can meet more than 80% of energy needs while lowering operational costs. The integration of energy storage systems and artificial intelligence also plays an important role in optimizing energy supply and demand in urban areas [154]. The development direction of the IKN that adopts renewable energy sources, smart grids, and high-resilience city designs is in line with global practices toward low-carbon cities. This concept not only improves energy efficiency and reduces dependence on fossil fuels, but also strengthens Indonesia's position as a pioneer of high-tech green cities in the Southeast Asian region.

In addition to the energy sector, the green transportation system is one of the main components in the application of environmentally friendly technology in IKN. All modes of public transportation are planned to be electric and hydrogen-based, including buses, official vehicles, and city public transportation. The implementation of this low-carbon transportation system is in line with the global trend toward clean mobility. A study by [155] confirms that the switch to electric vehicles is an effective strategy to reduce urban carbon emissions by up to 60%, despite still facing challenges in the battery life cycle and charging infrastructure. The construction of charging stations at various strategic points and the provision of bicycle and pedestrian lanes will strengthen the sustainable mobility system in the IKN. A global study [156] highlights that the integration between electric transportation, green fuels, and transportation digitalization can reduce energy consumption by up to 45% and accelerate the transition to low-emission cities. Similar approaches have been applied in high-tech urban areas in Europe and Asia, showing significant results in improving transport efficiency and air quality. In policy, the implementation of the green transportation system in the IKN reflects the circular economy paradigm that is increasingly adopted by modern cities. [157] in the Journal of Cleaner Production emphasized that the application of the circular economy model in the transportation and waste management sectors can create energy-independent and low-waste net-zero neighborhoods. The application of this concept is very relevant to the Indonesian government's efforts to build a resilient and climate-resilient urban ecosystem. In the context of water and waste management, IKN adopts the concept of a closed-loop system through waste-to-energy technology and integrated water treatment. Solid waste is sorted from source and converted into electrical energy, alternative fuels, or recycled materials, as recommended [158] research on the implementation of a circular economy in Singapore, which successfully reduced waste to landfills by up to 30% and improved energy efficiency nationally. For water management, the implementation of rainwater storage and recycling systems in IKN is in line with the results of the Major Green Technology Innovation and Implementation Mechanisms study [159], which shows that the integration of smart water technology can save up to 40% of municipal water consumption and increase water resource resilience. The waste-to-energy technology applied in the IKN also received empirical support from [156] research which highlighted that the waste-to-energy conversion system can reduce greenhouse gas emissions by up to 25% compared to conventional stockpiling methods. This technology integration strengthens the smart and resilient city paradigm, where each infrastructure sector is interconnected in a sustainable circular system. The implementation of green transportation, clean energy systems, and sustainable waste management makes IKN a transformational project toward a low-carbon city based on technological innovation. This concept puts Indonesia on a par with countries that have already implemented the integration of energy systems and green mobility, such as Singapore and South Korea, with an orientation toward zero-emission cities by 2045.

IKN also implements the concept of green building in the entire planning and construction process. Every public building is designed following energy efficiency and water resource conservation standards. The use of eco-friendly building materials such as low-carbon concrete, VOC-free paints, and natural ventilation systems is an integral part of architectural design. In addition, the application of BIM technology and digital twins helps ensure material efficiency, reduce construction waste, and enable real-time quality and environmental impact monitoring. In the aspect of spatial planning, IKN applies the concept of forest city which places ecological balance as the core of regional planning. About 65% of the total area of the IKN will be maintained as green areas, including conservation forests, urban parks, and ecological corridors. Satellite-based monitoring technology and IoT sensors are used to control vegetation health, air quality, and biodiversity. This approach not only preserves Borneo's native ecosystem, but also serves as a model for future urban development that is in harmony with nature. In addition to focusing on physical technology, the development of the IKN also emphasizes digital technology for environmental and social governance. Through the smart city management system platform, the government can integrate environmental, transportation, energy, and social data into a single decision-making system. For example, air quality and ambient temperature sensors will be connected to climate change early warning systems, while traffic and energy consumption data are analyzed using artificial intelligence (AI) to improve resource efficiency. Thus, the IKN is not only built in a green physical way, but also managed digitally sustainably. According to [160], the application of sustainable construction technologies such as prefabrication, green materials, and renewable energy can reduce energy consumption by up to 40% in high-rise buildings. The use of BIM and digital twins in the IKN also strengthens the efficiency of construction design and supervision. [138] explained that the implementation of digital twin-driven circular economy in the construction sector can increase material efficiency by up to 30% and support the principle of triple bottom line sustainability (economic, social, environmental). In addition, the integration of AI and IoT into BIM systems has been shown to accelerate the detection of design errors and energy optimization of buildings as discovered [161]. In the context of sustainable architecture, [162] highlight the importance of building envelope innovation with digital technology and project control to achieve maximum energy efficiency in urban areas. A similar approach is also adopted in the IKN through the use of sensors for thermal monitoring and adaptive ventilation. In urban spatial planning, the forest city concept is applied by maintaining 65% of the IKN area as green space. This strategy is in line with the idea of building ecologically resilient cities put forward [163], who affirm that the integration of AI-powered digital twins and IoT can monitor vegetation, air quality, and environmental dynamics in real-time to maintain ecosystem balance. In addition to the physical approach, IKN also implements a smart city management system that integrates environmental, energy, and social data into a single decision-making platform. [134] developed a BIM-based 5D Digital EIA framework to assess ecological impacts in a sustainable and dynamic manner, an approach relevant to the governance of the capital city. In data and resource management, the application of AI and big data analytics helps optimize energy consumption and predict peak loads. A study [164] emphasizes the importance of digital-based carbon tracking systems to monitor emissions across the urban sector as part of a global commitment to net-zero emissions. The approach taken at IKN shows a holistic integration of physical and digital technologies: BIM and digital twins for construction efficiency, AI and IoT for environmental monitoring, as well as the concept of forest cities for ecological conservation. Models like this reflect a new direction of future urban development that combines ecological sustainability, energy efficiency, and digital intelligence as a single system.

However, the application of green technology in the IKN cannot be separated from various challenges. One of them is the huge initial investment needs and limited technical capacity in the application of new technologies. In addition, the success of the green city concept depends on public awareness and participation in maintaining the sustainability of the built system. Therefore, the government needs to ensure public education and community empowerment so that residents understand the benefits of green technology and are actively involved in its implementation. The development of the IKN has become a real laboratory for the application of green technology in Indonesia. The integration of technological innovation, smart governance, and ecological awareness is expected to create urban development models that are low-carbon, resilient to climate change, and oriented toward long-term well-being. If successful, the IKN can become a global example of how developing countries are able to combine technological advances and environmental conservation in one sustainable development framework.

11.4. Challenges and Opportunities in Environmental Technology Implementation

The application of environmental technology is an important step in supporting sustainable development. However, the implementation process does not always go smoothly. In many countries, including Indonesia, various challenges arise from the technical, economic, social, and institutional aspects. On the other hand, there is a great opportunity to drive transformation toward a greener and more efficient development system. By understanding these challenges and opportunities in a balanced manner, planning and development of environmental technology can be strategically directed to provide maximum benefits for society and the environment. One of the main challenges in the implementation of environmental technologies is the high initial investment cost.

Most green technologies, such as renewable energy systems, waste treatment infrastructure, or low-carbon materials, require more upfront capital than conventional technologies. Despite having lower operational costs in the long run, barriers to initial financing often make businesses or local governments hesitant to adopt them. In addition, limited access to green funding schemes and low understanding of financial institutions on the risks and economic potential of environmental projects have also slowed down the adoption of these technologies. Research on Sustainable Finance, Strategies and Tools to Manage Climate Risk [165] explains that large initial capital costs and low fiscal incentives are the main barriers to accelerating the adoption of green technologies, especially in developing countries. While green technologies offer long-term operational cost savings, many projects fail to attract investors due to high initial risks and limited access to green financing. A study [166] shows that similar constraints occur in the energy sector and heavy industry in Ghana, where the transition to a low-carbon economy is hampered by the lack of innovative investment models and effective incentive policies. From an institutional perspective, the lack of understanding of financial institutions on the risks and economic potential of environmental projects slows down the flow of investment into the green sector. This is emphasized [167] who found that policy coordination between financial institutions and regulators greatly determines the success of green investments in developing countries. Instead, the adoption of sustainable financial instruments such as green bonds and carbon taxes has been shown to encourage investment in the renewable energy sector in Europe and Asia. However, various studies confirm that behind these challenges there is a great opportunity to drive transformation toward a green economy. In addition, international policies that support green taxonomy and carbon disclosure standards as discussed in the Sustainable Finance-Investment Interaction Model [167] can accelerate the harmonization of sustainable finance systems in developing countries. Although the application of environmental technology faces various structural and financial challenges, the opportunities for green economic transformation remain wide open. Through consistent policy support, financing innovation, and cross-sectoral collaboration, sustainable development based on environmental technology can be a key pillar of the transition to a low-carbon economy in the future.

In technical and infrastructure, another challenge is the limited capacity of human resources and supporting infrastructure. The application of environmental technologies require specialized expertise in the design, operation, and maintenance of systems. The lack of experts and testing laboratory facilities is a major obstacle, especially in areas that do not have access to advanced technology. In addition, inadequate basic infrastructure — such as power grids, transportation, or data systems — can hinder the adoption of digital-based technologies or renewable energy. This shows the importance of capacity building and investment in research and technical education in the environmental sector. Regulatory and institutional aspects are also crucial obstacles. Many environmental policies are still partial and do not fully support green technology innovation. For example, the long licensing process, overlap between institutional authorities, or the absence of national technical standards for environmentally friendly products. As a result, industry players often experience legal uncertainty and difficulties in implementing new technologies. In addition, weak coordination between government agencies can cause environmental policies to run out of sync between the central and regional governments. Institutional reforms are needed that encourage the integration of policies across sectors, such as energy, transportation, industry, and spatial planning, so that environmental technologies can develop systematically. A study [168] in South Africa shows that the success of the sustainable energy transition is highly dependent on the institutional capabilities and technical capacity of local governments to drive technological innovation and adaptation. In addition, inadequate basic infrastructure, such as power grids, transportation, and data systems, are barriers to the implementation of digital technologies and clean energy. [169] emphasizes that weak institutional coordination and the low quality of energy data in Uzbekistan are slowing down the implementation of large-scale renewable energy projects, despite the very high potential of natural resources. Similar conditions were also found in Africa [170], where infrastructure readiness and technical capacity of companies are major factors in attracting sustainable investment. In the Indonesian context, [171] highlight the importance of energy law and policy reforms to strengthen access to renewable technologies in rural areas, as well as expand technical training for local communities to be able to manage community-based energy systems. This shows that human capacity building must go hand in hand with investment in energy infrastructure and technical education systems. Regulatory and institutional aspects are also crucial obstacles. Many environmental policies are still partial and do not support integrated green technology innovation. [172] reveal that regulatory weaknesses and unbalanced risk distribution in public-private partnerships often hinder the development of low-carbon projects in Sub-Saharan Africa. A similar case occurred in Nigeria, where weak law enforcement and policy overlap slowed the implementation of renewable energy, although political support increased significantly. [173] affirm the need for an integrated legal framework that facilitates cross-sector coordination and accelerates the licensing process of green projects. From a global perspective, institutional capacity and energy governance play a major role in determining the success of the environmental technology transition. A study [174] in Kenya shows that the success of green electrification depends on partnerships between governments, research institutions, and the private sector in building adaptive technical and regulatory capacity. In addition, political and security factors can also affect the successful implementation of environmental policies. [175] found that in post-conflict regions such as Kosovo, political instability and weak inter-agency coordination are major obstacles to the implementation of the EU's green policies. Strengthening human resource capacity, regulatory reform, and cross-sectoral institutional governance are the main keys to accelerating the application of environmental technology. This strategy is in line with the findings of [170] that investments in technical education, smart energy systems, and national policy coordination will create an innovation ecosystem that supports green development in developing countries.

From a social and cultural perspective, challenges arise in the form of low public awareness and participation in the importance of environmental technology. Some people still view green development as expensive or not urgent. Patterns of consumptive behavior, lack of environmental education, and inefficient resource management habits become psychological and social obstacles. In fact, the successful implementation of environmental technology is highly dependent on public support — from recycling behavior, energy saving, to the maintenance of green facilities in residential environments. Therefore, environmental education and socialization programs need to be improved to build collective awareness and change people's behavior. Although the challenges are great, the opportunities for environmental technology development in Indonesia and the world are very wide. One of the key opportunities is the increasing global commitment to reducing carbon emissions and climate change. International agreements such as the Paris Agreement and the 2030 Agenda Sustainable Development Goals (SDGs) encourage countries to invest in clean technologies. This opens up access for Indonesia to get financial support and technology transfer from international partners. Green financing schemes such as the Green Climate Fund or carbon trading also provide incentives for the public and private sectors to invest in sustainable projects. In addition, great opportunities arise from the advancement of digital technology. Innovations in the fields of IoT, AI, big data analytics, and sensor technology allow environmental surveillance and management to be carried out more efficiently and transparently. For example, real-time air and water quality monitoring systems, smart waste management, and data-driven decentralized energy systems. Digital technology can also be used to strengthen environmental governance through data transparency and community participation. Thus, the industrial revolution 4.0 not only focuses on economic efficiency, but also has great potential to support ecological sustainability. Research by [176] shows that social resistance to green technology is often influenced by cultural norms, risk perceptions, and trust in governments or industry players. Effective public education programs play a major role in shaping recycling behaviors, energy saving, and awareness of green facilities in residential environments [177]. However, behind these challenges there are great opportunities for the development of environmental technology in Indonesia and the world. The global commitment to reducing carbon emissions and adapting to climate change embodied in the Paris Agreement and the 2030 Agenda SDGs has created ample space for international collaboration. Developing countries can now access green finance through schemes such as the Green Climate Fund and carbon credit trading that encourage private investment in clean energy projects and the circular economy [178]. This strengthens energy independence while increasing people's ecological awareness. Furthermore, the integration between digital technologies, social innovation, and adaptive environmental policies can form an inclusive sustainability ecosystem. According to [179], digital transformation accompanied by public participation has the potential to accelerate the achievement of global green development targets through cross-sectoral collaboration between governments, academia, industry, and civil society. The industrial revolution 4.0 is not only about economic efficiency, but also a strategic means to strengthen ecological sustainability. Changing people's behavior through education and participation, supported by advances in digital technology and global support for green funding, makes the future of environmental technology even more promising for Indonesia and the world.

Another opportunity comes from the potential of Indonesia's natural and biological resources. High biodiversity opens up opportunities for the development of bio-based eco-friendly materials, such as bioplastics, biofuels, and natural building materials. In addition, the abundant availability of renewable energy — such as solar, wind, geothermal, and biomass — makes Indonesia potentially a leader in the clean energy transition in the Southeast Asian region. To maximize this opportunity, sustainable research and innovation support and synergy between the government, universities, and the industrial sector are needed. Finally, there is an opportunity for a shift in the economic paradigm toward a green and circular economy. More and more companies and consumers are demanding products with a low carbon footprint and sustainable production processes. This trend opens up space for business actors to innovate and create added value through resource efficiency and recycling. In addition to providing environmental benefits, this approach also strengthens the competitiveness of the national industry in a global market that is increasingly environmentally conscious. The challenges in the implementation of environmental technology are indeed complex and multidimensional. However, every challenge holds opportunities for the birth of new innovations. With consistent policy support, human capacity building, cross-sectoral collaboration, and high public awareness, the application of environmental technology can be a key driver for sustainable development. In the future, countries that are able to integrate green technology in all aspects of development will become leaders in creating a cleaner, resilient, and prosperous future. Environmental technology plays a very important role in realizing sustainable development that is oriented toward a balance between economic, social, and ecological interests. Through the application of the right technological innovations, development activities no longer have to be contrary to nature conservation, but can support and strengthen each other. Various applications of environmental technology in the fields of infrastructure, transportation, energy, and natural resource management have shown that technological advances can be a real solution in reducing pressure on the environment while improving people's quality of life. From the discussion that has been described in this chapter, it can be seen that the application of environmental technology in infrastructure projects has a significant positive impact. The use of renewable energy systems, construction waste management, and the implementation of digital-based smart monitoring are able to reduce emissions and resource use efficiency. This technology makes development projects not only focus on physical outcomes, but also consider ecological sustainability in every stage. Thus, green infrastructure development is not just a global demand, but an urgent need for Indonesia to ensure that economic growth does not sacrifice the environment.

In addition, the use of environmentally friendly materials in road engineering is one of the strategic steps in supporting the transformation toward a sustainable transportation system. Through innovations such as recycled asphalt, the utilization of industrial waste, and bio-based materials, the road construction sector not only contributes to the reduction of carbon emissions, but also to cost efficiency and increased durability of infrastructure. This approach shows that environmental technology has great potential in creating effective and economical solutions for national development needs. The case study of IKN development shows the application of the concept of a green and smart city integrated with green technology comprehensively. Starting from renewable energy, low-emission transportation systems, circular-based water and waste management, to the implementation of smart city systems that utilize digital technology for environmental monitoring, all are designed to support sustainable urban life. The IKN is concrete proof that the vision of modern development can be realized without sacrificing ecological balance, as well as being a model for other cities in implementing sustainability principles in real terms.

However, it is necessary to realize that the process of implementing environmental technology in Indonesia still faces various obstacles. Financial barriers, limited technical knowledge, weak institutional coordination, and low public awareness are still the main inhibiting factors. Therefore, there is a need for strong policies, incentive support, and cross-sectoral partnerships to encourage the acceleration of green technology adoption. Capacity building of human resources, local research and technology development, and collaboration between government, industry, academia, and the community are the main keys to success in overcoming these barriers. Nonetheless, great opportunities are open for the development of environmental technologies in the future. Advances in digital technology, increasing global awareness of climate change issues, and national commitment to clean energy transition provide positive momentum for the implementation of sustainable innovation. Indonesia, with its wealth of natural resources and biodiversity, has great potential to become a pioneer in the development of environmentally friendly materials, renewable energy, and green development models at the regional and global levels. The application of environmental technology is not just a technical effort to repair natural damage, but is a paradigm transformation of development. Development based on green technology will create a more efficient economic system, a healthier society, and a more sustainable environment. Therefore, the integration of technological innovation, public policy, and social awareness is an important foundation in realizing a sustainable and competitive future of Indonesia's development. This chapter affirms that the future of nation-building lies in our ability to make wise use of technological advances—not to conquer nature, but to live in harmony with it. With strong commitment, cross-sector collaboration, and sustainable innovation, Indonesia can be a real example for the world in realizing green, smart, and sustainable development.

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CHAPTER 12

VEHICLE OPERATING COST AND VALUE OF TIME

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Transportation is one of the vital elements in supporting economic growth and equitable regional development. The success of a transportation system is not only measured by the availability of road infrastructure, but also by the level of cost efficiency and time required in the travel process. In this context, vehicle operating costs (VOC) and Value of Time are two important indicators that are interrelated in assessing the performance and effectiveness of the transportation system. The VOC describes the economic burden borne by vehicle users due to road conditions and operational factors, while the time value reflects how much people value the importance of time in their trips. An analysis of these two aspects provides a deeper understanding of the relationship between infrastructure quality, transportation efficiency, and their impact on the regional economy. When road conditions deteriorate, the VOC increases and travel times become longer, which ultimately decreases the productivity and competitiveness of an area. On the contrary, good road infrastructure can lower the VOC and save travel time, thus providing direct economic benefits to the community. Therefore, understanding the VOC and the value of time is an important basis in planning, evaluating, and formulating public policies in the transportation sector.

This chapter discusses four main interrelated topics. First, VOC based on PCI which explains how the physical condition of the road affects the efficiency of travel costs. Second, The Value of Travel Time and its Impact on Regional Economies, which highlights how travel time plays a role in people's productivity and well-being. Third, a Case Study of Travel Costs in Kalimantan, which illustrates the real conditions of the influence of infrastructure on travel costs and time in regions with complex geographical challenges. Finally, the Relationship Between VOC and Public Policy, which discusses the relationship between the results of transportation economic analysis and the formulation of equitable and sustainable development policies. Through the discussion in this chapter, it is hoped that it can be understood that improving transportation efficiency is not only a technical issue, but also an economic and social strategy that has a wide impact. An understanding of VOC and the value of time will help planners, academics, and policymakers formulate concrete steps toward a more efficient, fair, and community-welfare-oriented transportation system.

12.1. Vehicle Operating Cost Analysis (VOC) Based on PCI

VOC are a measure of the total expenses incurred by vehicle users in traveling on a road. VOC components include fuel costs, lubricants, vehicle depreciation, tires, maintenance costs, and driver costs. VOC s is often used in transportation analysis to assess the efficiency of road infrastructure and determine road network improvement policies. One of the approaches that is often used to assess the influence of road conditions on the VOC is the PCI. PCI is a numerical indicator on a scale of 0 to 100, where a value of 100 indicates very good road conditions and 0 means very damaged. The relationship between VOC and PCI is inverse (negative). The lower the PCI value, which means that the road condition deteriorates, the higher the VOC that must be issued by vehicle users. Bumpy, pothole, or uneven road conditions cause vehicles to work harder to maintain speed and stability, thereby increasing fuel consumption and accelerating the wear and tear of vehicle components. In this context, a PCI-based VOC analysis can be used to determine the priority of road improvements by considering the economic impact on users. International studies show that poor pavement conditions lead to increased fuel consumption and accelerated wear and tear of vehicle components, thereby significantly increasing the cost of road users. [1] developed a zero-one programming-based road maintenance optimization model that considers travel time savings and fuel consumption as a function of PCI. [2] reinforced these findings through the integrated Life Cycle Cost Analysis (LCCA) and Life Cycle Assessment (LCA) models, which showed that improving the quality of road pavements can reduce lifecycle costs by up to 25% while reducing environmental impact. The life-cycle cost-based approach was also extended [3], who assessed the cost efficiency of steel bridges by considering the user cost and maintenance components, showing that construction quality has a direct effect on long-term VOC . Meanwhile, [4] used the DPSIR-SD framework to assess the sustainability of roads in Australia and asserted that the reduction in PCI systematically increases social costs due to increased VOC and user travel time. Research based on road network optimization shows a strong relationship between road conditions, travel time, and user cost efficiency. [5] explain that the determination of optimal preventive maintenance time can reduce total user costs by up to 18% if done before the PCI value drops below the threshold of 70. [6] also add that the integration between economic analysis (LCCA) and environmental (LCA) provides a quantitative basis for determining actual operational costs over the life of road services. In addition, [7] emphasize that social costs such as vehicle operating costs and traffic delay costs need to be included in the calculation of the efficiency of road construction projects, as they represent indirect economic impacts on society. [2] and [1] also affirm that parameters such as traffic volume, pavement roughness, and road surface area are the main determinants of VOC , where small variations in pavement conditions can lead to a cost spike of up to 15% on traffic-congested networks.

Methodologically, PCI-based VOC analysis is carried out by collecting field data on road conditions, vehicle characteristics, and actual travel costs. The data is then used to create an empirical model that illustrates the relationship between the level of road damage (PCI value) and the operational cost of the vehicle. For example, on roads with PCI 80 (good), vehicles may only consume 8 liters of fuel per 100 km, while on roads with PCI 40 (moderate damage), fuel consumption can increase to 10–11 liters per 100 km. The difference in consumption shows the magnitude of the influence of road conditions on vehicle efficiency. In addition to fuel, another cost component that is also sensitive to the PCI value is vehicle maintenance. Damaged roads accelerate the wear of tires, suspension, and steering systems, thereby increasing the cost of periodic maintenance. The cumulative impact of these increased costs is not only felt by individuals, but also by the logistics and public transportation sectors. Therefore, road maintenance with the aim of increasing the value of PCI can be considered a form of economic investment that provides long-term benefits through VOC savings for the community. In transportation planning, the VOC based on PCI is often used as the basis for cost-benefit analysis. When a road improvement project is planned, the decrease in VOC due to the increase in PCI is calculated as an economic benefit that can be compared to the cost of development. The results of this analysis help determine the economic feasibility level of the project. For example, road repairs that increase the PCI from 60 to 90 can lower the VOC by 25–30% depending on the type of vehicle, thereby improving travel efficiency and lowering the economic burden of the user. An empirical study [8] using the Highway Development and Management (HDM-4) model to correlate road surface quality with fuel consumption, found that an increase in the riding quality index can reduce fuel use by 2.32% in India's urban road network. Similar results were obtained [9], who showed that the increase in axle loads due to heavy electric vehicles accelerated the decline in PCI by up to 50%, resulting in a significant increase in user costs and energy consumption of urban road networks. In addition to fuel, the cost of maintenance and replacement of vehicle components is also very sensitive to PCI values. Bumpy roads accelerate the wear of tires, suspension, and steering systems. [2] through the combined LCCA and LCA models, confirmed that road surfaces with a rough texture increase total operating costs by up to 15% compared to smooth-surface roads, while increasing life-cycle carbon emissions. Follow-up research [1] developed a network optimization model based on zero-one programming, which links travel time savings and fuel consumption to PCI values directly, and shows up to 30% efficiency improvement on segments with timely maintenance. In the context of cost-benefit analysis, road repairs that increase the PCI from 60 to 90 can reduce the average

VOC by 25–30% depending on the type of vehicle and traffic conditions. This is in line with the findings of [10], which combine economic and environmental approaches in determining the optimal timing of road maintenance, suggesting that PCI-based decisions can significantly reduce road user costs while maintaining resource sustainability. From an infrastructure lifecycle perspective, [5] proved that maintenance delays after PCI drops below 70 increase total user costs by up to 18%, demonstrating the importance of early intervention based on road condition data. In general, PCI data collection is carried out through visual surveys or automated pavement condition survey (APCS) technology that measures the level of cracking, deformation, and surface unevenness. These PCI values are then used in mathematical or econometric models to predict VOC as a function of road conditions. Research by [10] and [2] shows that parameters such as traffic volume and roughness index (IRI) play a role as mediating variables that affect the PCI–VOC relationship. Thus, increasing the value of PCI through road maintenance not only has an impact on reducing individual costs, but also provides macro benefits in the form of logistics efficiency and increased regional productivity. Therefore, in modern transportation planning, PCI-based VOC analysis is not only assessing technical efficiency, but also an important instrument in determining public investment priorities. Road repairs that increase PCI are not just infrastructure activities, but economic investments that generate returns in the form of vehicle cost savings, reduced travel time, and sustainable improvement of regional economic performance.

Furthermore, this approach provides a scientific basis for policymakers in determining road investment priorities. Roads with low PCI values and high traffic volumes are usually prime candidates for improvement, as the potential for a reduction in VOC in those sections will have the greatest economic impact. Thus, the analysis of the VOC based on PCI is not only a technical tool, but also a strategic instrument to support sustainable transportation infrastructure development policies. It is important to understand that controlling VOC through PCI upgrades is an efficient step to achieve a more economical, environmentally friendly, and convenient transportation system for users. This approach is also in line with the principles of energy efficiency and reduction of carbon emissions, as improved road conditions contribute to a reduction in fuel consumption and air pollution. Therefore, the integration between VOC and PCI analysis can be a key performance indicator in the management of national and regional road networks. According to research [8], the implementation of condition-based maintenance strategies can reduce fuel consumption by up to 2.3% and save more than 0.12 million liters of fuel per 1000 vehicle-km through increased PCI. A similar study [11] showed that the Analytic Network Process (ANP) method can help prioritize maintenance projects by considering socio-economic factors and cost efficiency of road users. Thus, PCI-based VOC analysis is not only technical, but also strategic in supporting sustainable transportation policies. The integration between economic, environmental, and social aspects in road maintenance has been highlighted [12], who emphasize the importance of a holistic measurement framework for assessing the social and environmental impacts of transportation infrastructure policies. In addition, [13] developed a multi-criteria decision-making model that assesses road projects based on energy efficiency, life-cycle costs, and environmental impact, thereby supporting more sustainable investment decision-making. The energy efficiency approach in PCI analysis is also in line with the findings of [14], who assert that innovations in road network management can improve capacity, safety, and reduce emissions without the need to build new roads. This is in line with a study [8] which showed that improving the quality of pavement can directly reduce vehicle CO_2 emissions due to better fuel combustion efficiency. In the context of global transport policy, research [15] highlights that the improvement in road infrastructure conditions contributes significantly to the decarbonization strategy of the transport sector, especially in developing countries. Meanwhile, the Springer Transport Transitions report [16] confirms that investments in PCI upgrades should be seen as part of Europe's clean energy transition and sustainable mobility. The integration of VOC and PCI analysis can be used as the main performance indicator in the management of national and regional road networks. This approach not only improves transportation efficiency, but also strengthens national strategies in energy efficiency, carbon emission reduction, and improved socio-economic well-being of communities through better quality and sustainable infrastructure.

12.2. The Value of Time in Travel and Its Impact on Regional Economies

Value of Time (VoT) is an economic concept that describes how much a person values the time he or she has in monetary value. In other words, VoT reflects the amount of money a person is willing to pay to save a certain travel time. This concept is important in the field of transportation economics because time is a finite resource that has real economic value. When a person spends more time on the road, productive time for work, rest, or social interaction decreases — which indirectly results in economic losses. In transportation planning, VoT is used to assess the efficiency of transportation systems and determine infrastructure investment priorities. For example, toll road construction projects, mass transportation, or road network improvements are often measured by how much travel time users can save. The more time saved, the higher the economic benefit of the project. VoT is also the basis for calculating users' willingness to pay toll rates or faster and more convenient modes of transportation. As such, VoT is not only theoretical, but also has practical implications in public planning and policy. The VoT is greatly influenced by various factors, including income levels, travel destinations, modes of transportation, and socioeconomic characteristics of users. A person with a high income usually has a greater VoT because every hour saved can be used for activities of high economic value. Meanwhile, travel for business purposes has a greater time value than leisure travel, because time in a business context is directly related to productivity. In the context of transportation modes, trips using private vehicles tend to have a higher time value than public transportation, due to the convenience and flexibility factors. In line with the view of [17], [18], the concept of VoT plays a central role in the cost-benefit analysis of transportation projects, as the travel time saved is considered as a quantitatively measurable socio-economic benefit. In modern transportation planning, VoT is used to assess the efficiency of transportation systems and determine infrastructure investment priorities. Projects to build toll roads, mass transportation systems, or improve the quality of road networks are often measured by the VoT saved by users. The study [19] shows that improving the reliability of traffic information for train passengers can reduce effective travel time and increase the social value of public transportation investments. Meanwhile, [20] affirm that time value estimation is now a global trend in the evaluation of innovative transportation projects, especially for measuring the efficiency of high-tech based systems and transportation automation. The time value also serves as the basis for the willingness to pay (WTP) analysis, which is the willingness of users to pay to save travel time. An empirical study [21] in Central Java Province showed that variables such as income, frequency of toll use, and travel destinations have a significant influence on the WTP value of toll road users. In a broader context, [22] associate the VoT with the value of public electric vehicle supporting infrastructure. They found that electric vehicle users are willing to pay more for fast charging facilities because charging time savings are an important component of VoT. In addition to the economic aspect, VoT is also related to the social and sustainability dimension. [23] extend the traditional cost-benefit analysis approach by including the social benefits of sustainable modes such as cycling. The results suggest that longer travel times in active mode can have positive value through health and social benefits, which were not previously taken into account in conventional VoT models. In the context of public policy, the VoT is influenced by socio-economic factors, travel destinations, modes of transportation, and user characteristics. High-income individuals have greater VoT because every hour saved is directly related to their economic productivity. In contrast, travel for leisure purposes generally has a lower VoT than business travel. This is reinforced by the findings of [24], which show that high-income users are willing to pay more for the improvement of active mobility facilities in urban environments. VoT integration is also an important instrument in transportation tariff policy. Research [17] emphasizes that the benefits of saved travel time are often the biggest component in the economic assessment of toll road projects, mass transportation, and smart mobility systems. Therefore, VoT is not only an indicator of efficiency, but also the basis of a fair and proportionate tariff policy. Furthermore, [19], [20] reminded that the modernization of transportation systems based on digitization, real-time information, and automation actually increases the VoT because users are increasingly sensitive to travel delays and uncertainty. The VoT is not only a theoretical concept, but also a practical instrument in transportation planning and policy. The measurable use of VoT allows policymakers to determine the most economically and socially efficient investments. Furthermore, the integration of VoT with sustainability approaches can help internalize social and environmental benefits in transportation policies, in line with the transition to an efficient, environmentally friendly, and community-welfare-oriented mobility system.

The impact of the VoT on the regional economy is significant. Travel time efficiency is closely related to the productivity and economic growth of a region. Good transportation infrastructure can reduce travel time between regions, improve connectivity, and accelerate the flow of goods and services. Conversely, congestion, road damage, and inefficient transportation systems result in waste of time and energy, decrease productivity, and increase vehicle operating costs. This condition is a burden on the regional economy and hampers regional competitiveness, especially for regions that depend on land transportation. In addition to affecting individuals and economic sectors, the VoT also plays a role in assessing the social impact of a transportation policy. For example, the construction of new toll roads can save travel time for users, but also has the potential to create inequality of access for low-income groups who cannot afford toll rates. Therefore, in the analysis of public policy, VoT needs to be considered not only in economic efficiency, but also in social justice. The government can balance this by providing fast, safe, and affordable alternatives to public transportation so that the benefits of time savings can be felt equally. In transportation economics analysis, VoT is also used to calculate the time benefits saved in cost-benefit analysis (CBA). For example, if a transportation project can save 1 million travel hours per year with an average time value of IDR 30,000 per hour, then the economic benefits of the time saved reach IDR 30 billion per year. This figure can be compared to the project's investment cost to assess its feasibility. In this way, the VoT becomes an important indicator to measure the efficiency and effectiveness of public investment in the transportation sector. Furthermore, the increase in the VoT in society is often a sign of an area's economic progress. When people value time more, efficiency becomes part of the regional productivity culture. In the long run, this encourages economic transformation from a traditional system based on long working hours to a modern economic system based on efficiency and innovation. Therefore, transportation policies that pay attention to the VoT not only have an impact on the transportation sector itself, but also strengthen the foundations of sustainable regional economic development.

The VoT in travel is a key element in the economic analysis of transportation and regional planning. Through efficient travel time management, both through infrastructure improvements, public transportation systems, and traffic control policies, the government can increase productivity, strengthen connectivity, and grow the economic welfare of the community as a whole.

12.3. Travel Costs in Kalimantan

Kalimantan is an area with a very large geographical area and has diverse topographical characteristics, ranging from lowlands, hills, to swampy areas. This condition causes great challenges in the development of transportation infrastructure, especially the road network which is the main link between regions. Unlike the island of Java, which has a dense and relatively good road network, most of Kalimantan still faces limited infrastructure, both in quality and connectivity. This factor causes travel costs in Kalimantan to tend to be higher compared to other regions in Indonesia. Travel costs in Kalimantan can be analyzed through two main components, namely vehicle operating costs (VOC) and travel time value. Road conditions that are not optimal are the main cause of the high VOC . Roads that are potholed, bumpy, or unpaved cause increased fuel consumption and accelerate the wear and tear of vehicle components. For example, a vehicle that typically consumes 8 liters of fuel per 100 kilometers on smoothly paved roads can consume up to 11 liters on damaged roads. This increases travel costs, especially for the logistics and public transportation sectors that operate long distances. In addition, geographical factors and long distances between regions also increase travel costs. In some inland areas, transportation access still depends on dirt roads or a combination of land and rivers. When rainfall is high, many roads become difficult to pass, so travel time increases dramatically. In the context of the VoT, this increase in travel duration means considerable economic losses, both for individuals and the business sector. Logistics truck drivers, for example, take twice as long to cover the same distance as in areas with better infrastructure, resulting in decreased productivity and increased operational costs. In the regional economy, the high cost of travel in Kalimantan has a chain impact on the price of goods and services. Basic necessities transported from production areas to consumption centers become more expensive due to high logistics costs. This creates price disparities between regions and suppresses people's purchasing power, especially in remote areas. In addition, the high VOC also hinders population mobility, which in turn slows down local economic growth and regional market integration.

Damaged or unpaved roads increase fuel consumption and accelerate the wear and tear of vehicle components, as highlighted [25], who found that the quality of road infrastructure in tropical regions has a significant effect on community welfare and logistics costs. Empirically, suboptimal road conditions can increase fuel consumption by up to 30% compared to well-paved roads. For example, a vehicle that consumes 8 liters per 100 kilometers on smooth roads can increase to 11 liters on bumpy roads. The impact is exacerbated by the long distance between regions and the complex geographical terrain. [26] emphasized that limited accessibility in the East Kalimantan region, especially in the candidate area of the archipelago's capital city, is still a major obstacle in transportation planning and improving community mobility. In addition to physical factors, the issue of travel costs is also closely related to the integration of government policies and investments. [27] highlight the importance of the central government's role in developing road infrastructure as a driver of national economic growth. Through the MICMAC and Scenario Wizard approaches, this study shows that strengthening the strategic role of the government can accelerate inter-regional connectivity and reduce long-term travel costs. These findings are in line with the results of a global study that emphasizes the linkage between transport infrastructure and regional economic development. In the context of regional ecology and economy, the research of [28] confirms that sustainable spatial planning in Central Kalimantan is not only important for environmental conservation, but also for optimizing land use to support the logistics and transportation efficiency of rural communities. An integrated strategic spatial planning approach can help reduce travel costs by shortening access routes to economic centers, as well as reducing pressure on environmentally sensitive areas such as peat bogs. Borneo's complex geographical conditions also create a high dependence on alternative modes of transportation, such as rivers and ferries. As rainfall increases, many roads become impassable, resulting in delays in shipping goods and lost productive time. This is in line with the findings of [29], which show that the construction of new roads in eastern Indonesia has a dual effect: increasing economic access while also risking forest degradation if not planned properly. Thus, road construction policies must consider the balance between transportation efficiency and environmental sustainability. The economic impact of the high VOC and time value in Kalimantan is very significant. High logistics costs cause price disparities between regions and suppress people's purchasing power, especially in remote areas. In a global context, similar experiences have also occurred in the tropical forest regions of Cambodia and Southeast Asia, where road infrastructure investments without regard to the local context lead to economic spatial inequality, as outlined [25]. In Kalimantan, this phenomenon raises the urgent need for a region-based infrastructure planning strategy that takes into account local geographical and socio-economic conditions. Conceptually, effective road infrastructure improvements in Kalimantan can reduce national logistics costs, accelerate regional market integration, and encourage economic development in disadvantaged regions. However, as shown in the study [26], open data-based approaches and spatial technology need to be utilized to design targeted interventions in improving the accessibility of remote areas. The Kalimantan case study shows a close relationship between road infrastructure conditions, vehicle operating costs, travel time value, and regional economic growth. The imbalance between regions in road quality and connectivity is the main factor that determines economic efficiency and community welfare. Data-driven planning and sustainability-oriented policies are key in lowering travel costs in large archipelago regions such as Kalimantan.

Based on interprovincial VOC simulation data in Kalimantan, there is a significant variation in operational costs between routes due to differences in road conditions, average speed, and track length. The details of the calculation results are shown in Table 12.1 below.

Table 12.1. Vehicle Operating Costs (VOC) for Each Route and Province in Kalimantan

Province	Route Length (km)	Speed (km/h)	VOC / 1000 km (IDR)	Total VOC (IDR)
Route 1				
East Kalimantan	234	47.6	3,428,741	803,697
Central Kalimantan	942	54.6	3,372,454	3,176,852
West Kalimantan	419.4	50.6	3,396,204	1,424,368
Kalimantan Selatan	102.6	46.6	3,442,507	353,201
Route 2				
East Kalimantan	468.8	35.2	3,714,066	1,741,154
Central Kalimantan	823.7	36.3	3,677,785	3,029,392
West Kalimantan	479.7	36.8	3,662,073	1,756,697
Route 3				
East Kalimantan	720.31	38.8	3,603,917	2,595,938
Route 4				
East Kalimantan	749.2	41.6	3,536,725	2,649,715
North Kalimantan	52.7	41.5	3,534,475	186,267

From Table 3.1 it can be observed that the operational cost of the vehicle is greatly influenced by the average speed and length of the route. For example, on Route 2, the total VOC reached the highest value, which was around Rp 6.5 million, which was caused by the low average speed on the entire track (around 35–37 km/h). This indicates poor road conditions and demands heavier engine work, so fuel consumption and vehicle maintenance frequency increase. In contrast, on Route 1, with a higher average speed (46–55 km/h), the VOC per 1,000 km is relatively lower and travel efficiency is improved. The same pattern is also seen on Route 4 which crosses East Kalimantan and North Kalimantan. Although the route length reaches almost 800 km, the total VOC is relatively moderate compared to Route 2 due to the more stable road conditions and higher speeds. This data shows that the increase in average speed due to road repairs can significantly lower the VOC , while shorten travel time and improve logistics efficiency. Economically, the results of this simulation confirm that any increase in average speed of 5 km/h due to the improvement of road conditions can reduce the VOC by around 4–6%, depending on the type of vehicle and load load. Therefore, road quality improvement programs in Kalimantan not only have an impact on driving comfort, but also provide macroeconomic benefits, such as reducing logistics costs, strengthening regional supply chains, and reducing price disparities between regions. These findings show that road infrastructure management based on the PCI indicator and Vehicle Operating Cost (VOC) analysis is an important instrument in the formulation of efficient and sustainable transportation development policies.

The government's efforts to reduce travel costs in Kalimantan have been carried out through the construction and improvement of national roads as well as strategic projects such as the construction of the Trans-Kalimantan Road. The project aims to connect major cities and open access to previously hard-to-reach rural areas. Improving road quality is expected to be able to reduce VOC , speed up travel times, and strengthen economic connectivity between regions. Thus, the development of transportation infrastructure in Kalimantan is not only physical, but also strategic in increasing the economic competitiveness of the region. In addition to road construction, the policy of integrating transportation modes is also the key to the efficiency of travel costs in Kalimantan. The combination of land, river, and sea transportation can create a more cost- and time-efficient logistics system. For example, the use of large river routes such as the Mahakam and Barito Rivers as a distribution route for goods can reduce pressure on land transportation and reduce the total cost of travel. With this kind of integration, the movement of goods and people becomes more efficient despite the challenging geographical conditions. In the context of long-term planning, the study of travel costs in Kalimantan can be used as a basis for determining the priority of infrastructure development. Areas with high VOC values and large levels of economic activity should be a top priority for road network improvements. This approach not only takes into account transportation efficiency, but also provides fairness for development between regions. By reducing travel costs, the government can expand economic access, increase the distribution of regional production, and accelerate regional economic growth evenly. The Kalimantan case study shows that transportation efficiency is the main key in the development of large and scattered areas. Reducing travel costs is not only a matter of vehicle and road engineering, but also an economic strategy to create connectivity, reduce logistics costs, and strengthen regional economic structures. As transportation infrastructure improves, the VoT and productivity of the community increases, which ultimately accelerates the overall social and economic development of Kalimantan.

12.4. The Relationship Between VOC and Public Policy

Vehicle Operating Costs (VOC) have a very close relationship with public policy, especially in the fields of transportation, economy, and infrastructure development. The VOC reflects the economic burden borne by road users as a result of the prevailing infrastructure conditions, energy policies, and transportation regulations. Therefore, any change in public policy, both direct such as road construction and indirect such as fuel price policy, will affect the amount of VOC that must be paid by the public. On the contrary, the results of the VOC analysis are also important inputs for the government in formulating more efficient, fair, and sustainable policies. In the context of infrastructure development, public policies that focus on improving the quality of roads can directly reduce the VOC . Smooth and well-maintained roads reduce fuel consumption, reduce vehicle breakdowns, and speed up travel time. For example, when the government conducts routine maintenance programs for national and provincial roads, the PCI value increases, which means that road conditions are better. As a result, public spending on fuel and vehicle maintenance decreased, so purchasing power increased. Thus, road maintenance policies are not only technical investments, but also economic strategies that strengthen people's welfare. The study of [30] affirms the importance of the user-pay principle in financing road infrastructure so that the burden of transportation costs is more proportionate and sustainable. Public policies that focus on improving road quality have proven to be able to significantly reduce VOC . Roads with high PCI values reduce fuel consumption, vehicle maintenance costs, and travel time. [31] developed a transport transition financing policy model that shows that an efficient infrastructure investment strategy can reduce operational costs by up to 15–25% in the long-term scenario. Similar findings are put forward [32], who emphasize the importance of the heavy truck fleet electrification policy approach to reduce the total operational costs and carbon emissions of freight transportation. In addition, public transportation policies such as the development of the Bus Rapid Transit (BRT) system and distance-based fares are able to divert users from private vehicles to mass modes, reduce fuel consumption, and improve travel efficiency. The study of [33] shows that the BRT system in Vietnam provides economic benefits through time savings and reduction of external costs such as pollution and traffic accidents. On the other hand, [34] research highlights the importance of congestion pricing policies to regulate traffic demand and provide sustainable funds for new infrastructure development. Energy policy and fuel prices also play an important role in the size of the VOC . [35] found that an electric vehicle ownership model accompanied by fiscal incentives can reduce the Total Cost of Ownership (TCO) while reducing operational costs by up to 30% compared to conventional vehicles. This is reinforced [36], who analyzed vehicle electrification policies in Ireland and showed that despite the high initial costs, the long-term benefits for users and the environment are much greater. Effective public policies in lowering VOC s include not only the technical aspects of road maintenance, but also the structural transformation of the transportation system toward energy efficiency and sustainability. This approach emphasizes that infrastructure policies should be designed as long-term economic investments that improve regional competitiveness and community welfare.

On the other hand, public policies that do not pay attention to the operational aspects of vehicles can have negative economic impacts. For example, delays in road repairs or infrastructure budget restriction policies lead to a decline in the quality of the road network. As a result, the VOC increases as vehicles require more fuel and parts, while the travel time also becomes longer. This situation not only burdens vehicle users, but also increases logistics costs and prices of goods in the market. Therefore, the integration between fiscal, transportation, and regional development policies is essential to ensure that any public decisions produce an efficient economic impact. In addition to road construction, energy policy also has a big influence on VOC . Fuel pricing, energy subsidies, and regulations on environmentally friendly vehicles can change the structure of operating costs. When fuel prices rise, the VOC increases directly, especially for the logistics and public transportation sectors. However, if government policies encourage energy efficiency through the use of electric vehicles or alternative fuels, the VOC can be suppressed in the long run. This shows that environmentally oriented public policies can also provide economic benefits through savings in vehicle operational costs. A study conducted [37] confirms that public subsidy policies and appropriate transportation pricing strategies can improve social efficiency as well as reduce external costs such as air pollution and carbon emissions. Furthermore, energy policy plays an important role in determining the cost structure of the VOC . [38] suggest that a decarbonization scenario with the electrification of heavy vehicles in Sweden can lower the cost of transportation systems in the long run, although it requires a high initial investment in batteries and charging infrastructure. Meanwhile, research [39] confirms that the implementation of operational efficiency policies such as reducing empty trips and optimizing shipments can save logistics costs while reducing carbon emissions in the road transportation sector. In a broader context, [40] highlight that a national decarbonization strategy focused on transportation energy efficiency can reduce emissions by up to 70% without reducing people's mobility, by integrating vehicle electrification and the development of alternative fuels. Research [41] also shows that public policy investment in electric road infrastructure can be a "no-regret investment" step if accompanied by policies that ensure high utilization rates In addition to energy and infrastructure policies, [34] explained that transportation financing policies and road pricing systems also affect VOC and social justice. Mileage-based tariff systems can internalize the external costs of transportation while driving fuel use efficiency. On the other hand, [42] through a study in Saudi Arabia found that hybrid and electric vehicle incentive policies not only reduce emissions, but also reduce TCO in the long run, especially if the government provides financial support to suppress depreciation costs. Integration between fiscal, transport and energy policies is essential in controlling the VOC and creating a sustainable transport system. When public policies are directed to support energy efficiency, sustainable road maintenance, and the transition to low-emission vehicles, the resulting economic impact is not only in the form of operational cost savings, but also increased productivity and community welfare in the long run. The relationship between VOC, PCI, and VoT is an important basis for understanding how the quality of road infrastructure affects regional economic efficiency. In the context of public policy, this relationship explains how decisions in road construction, maintenance, and investment can have a direct impact on the economic performance of the community. To illustrate the mechanism of this relationship, here is a simulation diagram that shows how changes in PCI values affect VOC , VoT, and regional economic efficiency.

Figure 12.1 shows cyclic and conditional relationships between road conditions, VOCs, and regional economic efficiency. When the Pavement Condition Index (PCI) value is high—indicating the road is in good condition and smooth surfaces—the vehicle can operate efficiently with lower fuel consumption and minimal maintenance requirements. This significantly lowers the Vehicle Operating Cost (VOC). This decrease in VOC contributes to shorter travel times and an increase in Time Value (VoT), as road users and business actors can take advantage of more efficient travel time for other productive activities. The combination of low VOC and high VoT improves the efficiency of the regional economy, which is reflected in reduced logistics costs and increased economic competitiveness. Conversely, when the PCI value drops below 70, the road conditions deteriorate with the appearance of surface damage such as potholes or waves. This increases fuel consumption, accelerates the wear of vehicle components, and leads to an increase in VOC. At the same time, Value Time (VoT) decreases as travel time becomes longer and productivity decreases. The cumulative impact of this condition is an increase in logistics costs, a decrease in the efficiency of goods and human mobility, and a decrease in regional economic competitiveness. Thus, road conditions serve as a sensitive policy variable, which directly mediates the relationship between transportation infrastructure and macroeconomic performance. From a public policy perspective, this framework supports an evidence-based policy making approach. The government can use data on the relationship between PCI, VOC , and VoT to determine the priority of road maintenance on the sections that have the greatest economic impact. As described in research [43], the integration of economic indicators into infrastructure analysis allows for more efficient resource allocation as well as promoting sustainable economic growth. Therefore, combining VOC and VoT analysis in infrastructure planning is not only a technical approach, but also a policy strategy oriented toward efficiency, social justice, and economic sustainability.

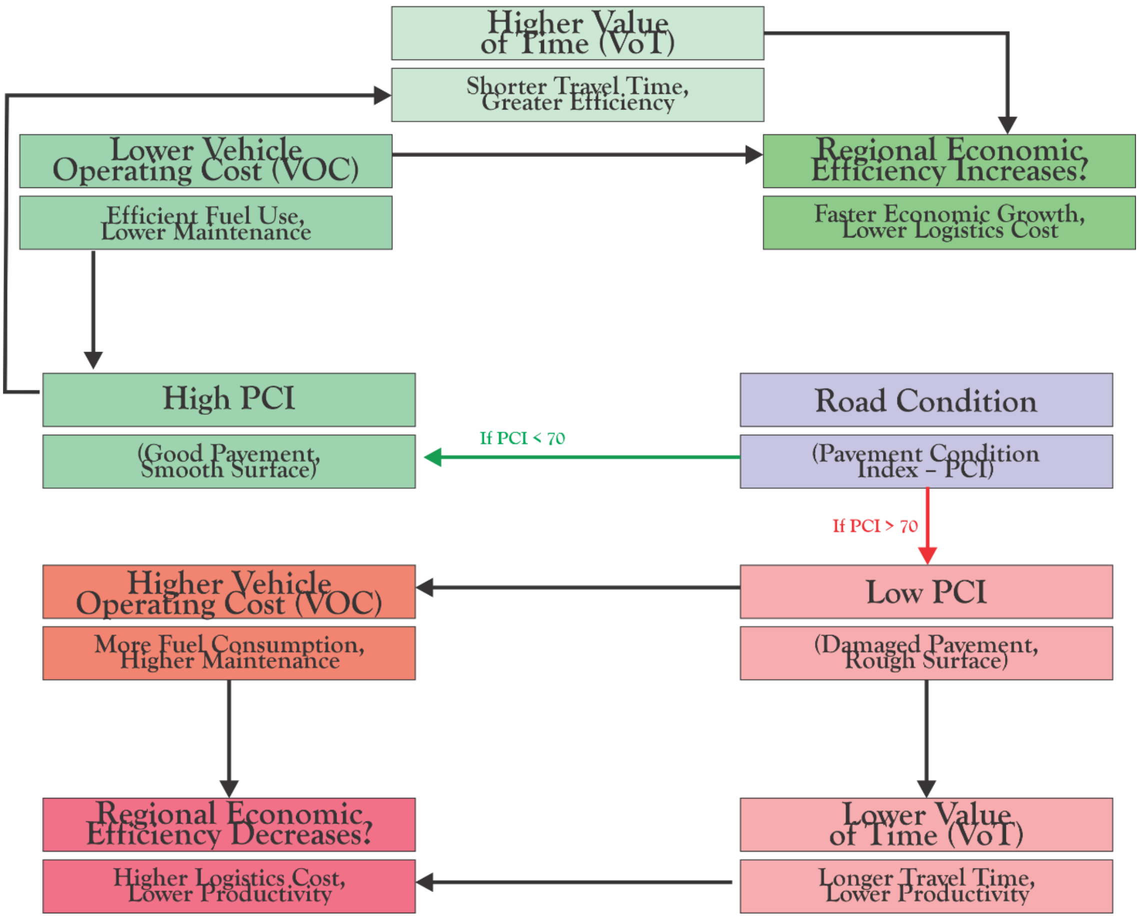

Figure 12.1. Simulation of the Relationship between Pavement Condition Index (PCI), Vehicle Operating Cost (VOC), and VoT on Regional Economic Efficiency (Source: Author's Conceptual Illustration, 2025).

The VOC is also an important tool in the evaluation of public transportation policies. For example, in determining toll road fares or congestion pricing systems, the government needs to weigh the balance between travel costs and the benefits of time saved by users. If the fare is too high, the user's VOC increases significantly and can decrease the interest in using the expressway, while if it is too low, the benefit of traffic regulation is not achieved. Therefore, VOC analysis helps the government determine the optimal and fair tariff level. Furthermore, VOC data is used to assess the socio-economic impact of transportation policies on different community groups. Low-income people, for example, are more sensitive to changes in travel costs because the proportion of transportation spending to their income is greater. Public policies that do not take this into account can widen social gaps. Therefore, VOC analysis plays an important role in inclusive policy planning, such as public transportation subsidies, village road programs, and improved connectivity in remote areas. Conceptually, the relationship between VOC and public policy reflects the application of evidence-based policy making principles, namely data-based decision-making and scientific analysis. By understanding how changes in infrastructure or energy prices affect the VOC , governments can design more effective and results-oriented policies. For example, investing in road improvements with priority on high-VOC sections can provide much greater economic benefits than building new roads in low-traffic areas. This approach emphasizes the importance of efficiency and fairness in the allocation of public resources. The integration between VOC analysis and public policy creates a productive policy cycle. VOC data provides a real picture of the economic condition of the road user community, while public policy determines the direction and quality of infrastructure changes that have an impact on the VOC itself. When these two elements are balanced, the national transportation system becomes more efficient, logistics costs decrease, economic competitiveness increases, and people's welfare is lifted. Therefore, the VOC is not only a technical indicator, but also a strategic instrument in the formulation of equitable and sustainable public policies. [44] assert that the optimal fare level depends on the distribution of the user's Value of Travel Time (VTT)—the higher the average VTT, the higher the acceptable fare without degrading the user's well-being. Congestion pricing policies also require high social acceptance to be effective. The study of [45] shows that public resistance is often the main cause of the failure of the implementation of this system, although it can theoretically significantly reduce travel time and VOC. A similar thing was observed [46] in Senegal, where the successful implementation of congestion tariffs depends on the level of social acceptance and public confidence in long-term economic benefits. In the context of social equity, [47] highlight that private vehicle control policies such as cordon tolls and fuel taxes tend to have a regressive impact on low-income groups, unless accompanied by subsidies for public transportation or redistribution of revenue from toll revenues. Meanwhile, [48] emphasize that tolling practices in the United States have evolved toward a tolling equity model, in which differential rates are applied based on the time, type of vehicle, and socioeconomic conditions of the user. In addition to the tariff aspect, the Road User Charging (RUC) approach is also an important strategy in infrastructure financing. [43] emphasize the need for a transparent usage-based tariff model to reduce cross-subsidies and ensure the fiscal sustainability of the transportation sector. This model is considered fairer because road users pay according to the level of use and its impact on infrastructure. Tariff policies must also consider spatial and social justice factors. [49] in his study of HOV and HOT lines in the US found that unequal access to toll lines can widen the mobility gap between groups of people. Data-driven approaches such as evidence-based policy making are crucial to balance traffic efficiency and social equity. In addition, [50] introduced a "trip pricing" model framework that allows cross-modal and destination comparisons of travel destinations to design optimal fares in a multi-objective manner, both in social welfare and system efficiency. This approach is relevant in the context of modern multimodal transportation that integrates private vehicles, public transportation, and sustainable modes. Conceptually, the relationship between VOC and public policy reflects the application of evidence-based policy making principles—where empirical data on operational costs, travel time, and demand elasticity are used to formulate efficient tariff and infrastructure policies. When the government targets investment in roads with high VOC , the economic benefits obtained are greater than the construction of new roads in low-traffic areas. This approach reinforces the principles of efficiency and fairness in the allocation of public resources. Ultimately, the integration between VOC analysis and public policy creates a productive policy cycle, lowers national logistics costs, increases economic competitiveness, and strengthens social welfare.

From the discussion in Chapter 12, it can be concluded that VOC and VoT are two main indicators that are interrelated in assessing the efficiency of the transportation system and its impact on the regional economy. The VOC describes the economic burden directly felt by users due to infrastructure conditions and public policies, while the time value reflects the economic value of the travel efficiency obtained by the community. Both are important cornerstones in transportation planning that is oriented toward social and economic benefits. VOC 's analysis based on the Pavement Condition Index (PCI) shows that good road conditions can significantly lower vehicle operating costs. This has a positive impact on improving transportation efficiency and reducing the economic burden of road users. Meanwhile, the VoT illustrates the importance of saving travel time for people's productivity and welfare. In the context of the regional economy, the more efficient the travel time, the higher the potential for regional economic growth.

A case study in Kalimantan shows that geographical challenges and uneven infrastructure conditions lead to high VOC and long travel times, which has an impact on increasing logistics costs and prices of goods. Therefore, the construction and improvement of road infrastructure in the region is not only a technical necessity, but also an economic strategy to reduce travel costs and improve connectivity between regions. Furthermore, the relationship between VOC and public policy demonstrates the importance of a data-driven approach in transportation policy formulation. Policies that pay attention to the results of VOC analysis and time values will produce more efficient, fair, and oriented decisions to improve people's welfare. Thus, good transportation management not only increases mobility, but also strengthens economic competitiveness and quality of life in a sustainable manner. Understanding the VOC and the VoT is key to the development of integrated, efficient, and inclusive transportation. The synergy between quality infrastructure, the right public policies, and awareness of the VoT will create a transportation system that not only supports movement, but also accelerates economic progress and community welfare throughout Indonesia.

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CHAPTER 13
INTEGRATED CASE STUDY: INTERDISCIPLINARY INTEGRATION

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Infrastructure development in Indonesia in the 21st century requires a paradigm shift from a sectoral approach to a cross-disciplinary integrative approach. In the midst of complex global dynamics, the success of development is no longer determined by one particular field of knowledge, but by the ability to combine diverse perspectives and expertise in a single mutually supportive work system. This chapter discusses in depth how the integration between industrial management, regional planning, and transportation engineering can be the foundation for a sustainable and highly competitive integrated development model. The integration of these three disciplines is crucial in answering development challenges in large areas such as Kalimantan, which has unique geographical conditions, abundant natural resources, and great potential as the center of Indonesia's new economic growth. In the context of national road construction in Kalimantan, inter-disciplinary synergies are becoming increasingly apparent: industrial management ensures project efficiency and smooth supply chains, regional planning directs development to suit the spatial structure and carrying capacity of the environment, while transportation engineering ensures that the infrastructure built is resilient, adaptive, and suitable for complex terrain conditions.

This chapter is structured to conceptually and applicative describe how cross-field integration can be realized in development practice. In the first part, real examples of the integration of industrial management, regional planning, and transportation techniques are discussed, highlighting the importance of interdisciplinary cooperation in creating an efficient and sustainable development system. The second part presents a case study of national road construction in Kalimantan, which is used as a concrete model for the application of an integrated approach in the field. Through this case, it can be seen how policies, technical planning, and project management can run in harmony to achieve national strategic goals. Furthermore, the third part presents a holistic evaluation of the social, economic, and environmental impacts of the development. This evaluation is important to understand the extent to which infrastructure development contributes to improving community welfare, regional economic efficiency, and ecosystem preservation. This kind of evaluation is also the basis for future policy and strategy improvements. Finally, the fourth section presents recommendations for similar projects in the future, emphasizing the importance of collaborative governance, technological innovation, local community empowerment, and the application of sustainability principles.

Kalimantan is an ideal example to illustrate the close relationship between infrastructure development and regional transformation. With a land area of more than 540,000 km^2 and a great potential for natural resources, the construction of national roads is not only a technical project, but also a socio-economic project that determines the direction of the region's growth. The Trans-Kalimantan network and interprovincial connectivity are the foundation for equitable development and strengthening the connectivity of the Nusantara Capital City (IKN) as the center of Indonesia's new government. This project shows that the success of development is not only measured by the number of kilometers of roads built, but also by the ability of the infrastructure to create economic added value, strengthen social cohesion, and maintain environmental balance. In addition, the development experience in Kalimantan shows that an integrative approach is not a mere theoretical concept, but a real need on the ground. The complexity of geographical conditions, logistical challenges, and socio-cultural diversity require strong and adaptive cross-sector coordination. Synergy between regional planners, transportation engineers, industrial economists, and local stakeholders is key in overcoming these barriers. The application of digital technology, geographic information systems (GIS), and data-based project management are also important factors in strengthening development efficiency and accountability. Thus, this Chapter 13 is not only intended as a technical case study, but also as a conceptual reflection on how infrastructure development can be a means of integrating science, public policy, and social interests. Through this integrated study, it is hoped that readers will gain a comprehensive understanding of the importance of cross-disciplinary synergy in building a competitive, inclusive, and sustainable future for Indonesia.

13.1. Integration of Industrial Management, Regional Planning, and Transportation Engineering

Modern regional development demands cross-disciplinary integration, especially between industrial management, regional planning, and transportation engineering. These three fields have strong functional interconnectedness in an effort to create efficient production, distribution, and sustainable spatial planning. Industrial management provides a systems approach to process and supply chain efficiency, regional planning establishes optimal spatial structures and land use patterns, while transportation techniques provide connectivity systems that allow for physical integration between production, distribution, and consumption centers. In the context of national development, the synergy of the three is key in increasing regional competitiveness and encouraging inclusive economic growth. Conceptually, industrial management focuses on optimizing production resources—both human, capital, and raw materials—in order to produce goods and services efficiently. This approach applies not only in the manufacturing sector, but also in the management of infrastructure and transportation projects. Principles such as lean management, supply chain integration, and value stream optimization are now being applied to design transportation systems that are efficient in terms of cost, time, and environmental impact. Regional planning then acts as a spatial framework that ensures the distribution of industrial and infrastructure activities in accordance with the carrying capacity of the environment and long-term development goals. Meanwhile, transportation engineering is a technical tool that translates spatial and economic strategies into the form of interconnected networks of roads, ports, airports, and multimodal modes of transportation. As a conceptual example, the development of an integrated industrial estate requires planning that combines the principles of supply chain management with zoning-based spatial planning and accessibility. Industrial management determines logistics needs, raw material flow, and efficient production capacity; regional planning establishes strategic locations taking into account connectivity, land availability, and ecological balance; Meanwhile, transportation engineering designs internal and external circulation systems that support the mobility of goods, labor, and public services. Without this cross-field coordination, industrial estates have the potential to grow inefficiently, causing congestion, regional inequality, and environmental degradation. This integration is also evident in the Transit-Oriented Development (TOD) development approach, which places transportation nodes as the main driver of economic activities and land use. The concept of TOD is a concrete example of how industrial management principles—such as operational efficiency and management of land economic value—are linked to regional planning strategies to create compact, efficient, and public-oriented cities. In the framework of transportation techniques, this requires analyzing network capacity, movement patterns, and transportation system design that is adaptive to regional growth. A study [1] shows that the integration of industrial supply chains and logistics services in the regional planning system is able to improve the competitiveness and efficiency of the regional economy through the "three-chain integration" model that emphasizes the interconnectedness between industrial innovation, added value, and spatial networks. This approach is increasingly relevant when associated with spatial planning based on digital technology. [2] emphasize that the integration of Geographic Information Systems (GIS) and data analytics strengthens public decision-making, including in transportation governance and regional planning, by leveraging machine learning to optimize resource distribution and infrastructure management. This spatial approach is in line with the research results of [3] who developed a spatial optimization strategy of the renewable energy industry chain in China by combining GIS analysis and integrated value chain theory to ensure a balance between economic efficiency and environmental sustainability. In the context of transportation engineering, the concept of integration is further strengthened by the application of Building Information Modeling (BIM) integrated with GIS. A study [4] shows that BIM–GIS integration is able to improve the efficiency of transportation infrastructure project management through design coordination, asset maintenance, and spatial data-driven decision-making. This approach not only optimizes project time and cost, but also strengthens cross-sector collaboration between planners, engineers, and project managers. As a conceptual example, the development of an integrated industrial estate requires planning that combines the principles of supply chain management with zoning-based spatial planning and accessibility. [5] through his book The AI City emphasizes the importance of integrating artificial intelligence in urban planning and transportation to connect industrial systems and urban mobility in one sustainable digital ecosystem. This approach is in line with the vision of smart city development that not only organizes space, but also organizes the interaction of people, technology, and resources. In addition, the application of cross-disciplinary integration is also seen in the development of Logistic Aerocity—the concept of an airport-based logistics city—which combines spatial analysis, multimodal transportation, and financial engineering in one infrastructure management framework. [6] show that this approach can optimize financial feasibility and operational efficiency through public-private partnerships and Life Cycle Cost analysis. In urban transportation planning practice, [7] found that GIS-based spatial analysis can be used to identify congestion points and design transportation capacity building strategies through short, medium, and long-term stages integrated with spatial planning policies. The results of this study show the importance of collaboration between transportation engineering and urban planning in improving the efficiency of the mobility network. Finally, the integration between industrial and transportation systems also demands innovation in regional governance. [8] propose a GIS-based multi-criteria evaluation approach to determine international logistics centers and ports by considering multimodal connectivity and spatial integration with industrial estates. This approach emphasizes that transportation policies and regional planning must be developed in an integrated manner so that industrial distribution chains can run efficiently, sustainably, and adaptively to global changes.

On a macro level, this inter-disciplinary integration also supports regional development policies based on economic corridors. Corridors like this are not only built to accelerate the flow of goods and services, but also to form new spatial structures that encourage the growth of industrial centers, logistics areas, and distribution centers. The industrial management here ensures the smooth running of the cross-regional production system; regional planning determines the zoning and hierarchy of activity centers; Meanwhile, transportation engineering designs connecting infrastructure that is in accordance with logistics needs and economic capacity. In the Indonesian context, the economic corridor approach is an important part of the Masterplan for the Acceleration and Expansion of Indonesian Economic Development (MP3EI) which combines the principles of industrial efficiency with equitable development between regions. It is also important to note that the integration of these three disciplines is not only technocratic, but also requires collaborative governance. Industrial management contributes to operational planning and project quality management systems, regional planning provides long-term strategic direction through spatial planning, while transportation engineering draws up measurable, data-driven technical planning. All three must be bound by a strong coordination mechanism, both at the policy and implementation levels. This is where the role of planning agencies, infrastructure regulatory bodies, and the private sector becomes important in realizing cross-disciplinary synergy. In addition, this integrative approach is the basis for sustainable development. Industrial efficiency that does not consider the spatial layout and capacity of the transportation network can lead to spatial inequality and environmental stresses. On the other hand, regional planning that does not take into account the logic of industrial supply chains and mobility needs can lead to economic inefficiencies. By combining economic, spatial, and technical analysis, planners can optimize the benefits of development for the wider community, while minimizing its negative impacts. At the project scale, this integration can be realized through an integrated planning mechanism from the feasibility study stage to operation. For example, in a toll road or port construction project, a planning study analyzes not only the technical aspects of construction, but also an economic analysis of the region, the potential of the industry to grow, as well as the projection of logistics movements. This approach allows every infrastructure investment decision to be part of a larger regional development strategy. On the other hand, the application of industrial management principles such as project management, risk assessment, and continuous improvement helps ensure that projects run on time, at the right cost, and in accordance with regional development goals. In the academic context, the relationship between these three disciplines has also become a focus in the systems thinking and integrated planning approaches. This approach views regions and industries as complex systems that affect each other, where transportation serves as the main link between sub-systems. This cross-field integration encourages the emergence of a new paradigm in development planning that is more adaptive to social, economic, and technological changes. Thus, the integration of industrial management, regional planning, and transportation techniques is not only a practical necessity in development, but also a conceptual strategy to realize a balance between economic efficiency, social justice, and environmental sustainability. This synergy is the main foundation for inclusive, productive, and sustainable national development.

Cross-country studies show that economic corridors designed with a systemic approach are able to improve supply chain efficiency and regional added value. For example, research [9] confirms that the development of transport corridors plays a role as a cross-border spatial planning instrument that strengthens industrial integration and regional supply chains through a combination of spatial and economic analysis. The corridor approach also demands integration between economic, spatial, and ecological dimensions. [10] proposed an integrated coastal corridor development model that emphasizes the integration of urban spatial planning, coastal industrial management, and transportation infrastructure to encourage sustainable development in coastal cities. In line with that, [11] highlights the importance of combining green infrastructure and dense spatial planning to strengthen urban ecological resilience as well as land-use efficiency, which is an important basis for modern green corridor design. In the context of regional economies, cross-disciplinary integration helps to optimize the relationship between industrial locations and transportation networks. [12] through the Land-Use Transport Interaction (LUTI) approach show how the development of rail corridors can change the pattern of industrial locations and intermodal logistics flows by strengthening spatial and economic connections. Such models show that the success of corridor construction depends on synchronization between spatial planning policies and transportation network design. On the project management side, inter-disciplinary integration demands collaborative governance involving planning agencies, infrastructure regulatory bodies, and the private sector. [13] asserts that highway projects in Europe show positive economic impacts in the form of increased investment and logistics efficiency, but require an environmentally friendly technology-based smart governance approach to suppress socio-ecological impacts. This emphasizes that the integration of policies and technological innovation is a crucial factor in ensuring the sustainability of corridor development. The integrative approach is also the foundation for the Logistic Aerocity model that combines land planning, transportation network design, and Life Cycle Cost-based financial analysis. [6] exemplify how this concept is able to bridge the limitations of public funding through public-private partnerships, while improving the efficiency of logistics space around airports. Furthermore, spatial integration and transportation are also strengthened by a multi-criteria approach. [14] used multi-criteria analysis to determine the axis of the transportation network in Mongolia, asserting that the success of the economic corridor depends on the selection of the route with the highest economic potential and optimal spatial connectivity. While Gao (2025) expands on this concept by integrating ecological analytics in urban spatial planning, emphasizing the importance of a balance between development and conservation. The application of industrial management principles such as project management, risk assessment, and continuous improvement ensures that corridor projects run on time, at the right cost, and in accordance with regional development goals. The study of [15] shows that the integration of rail transport with urban spatial planning can strengthen the economic value and heritage of the industry, provided it is supported by a multi-criteria analysis in each stage of planning. In addition, [11] highlights that the integrative approach is part of the new paradigm of systems thinking, where regions are seen as complex systems that affect each other between the economy, the environment, and mobility. This is reinforced [10] who emphasize the importance of collaborative governance and cross-sectoral policies in realizing sustainable corridor development. By combining economic, spatial, and technical analysis, any infrastructure investment decision can be part of a long-term regional development strategy that is adaptive to social and technological changes.

13.2. National Road Development in Kalimantan as an Integrated Development Model

The construction of national roads on the island of Kalimantan is one of the concrete examples of the application of the integration of disciplines between industrial management, regional planning, and transportation engineering (Fig. 13.1.). The Kalimantan region, with a land area of more than 540 thousand km^2 and consisting of five provinces, presents complex geographical and socio-economic challenges. The existence of the Capital City of the Archipelago (IKN) in East Kalimantan makes the development of the national road network not only function as a means of transportation, but also as the backbone of regional development, regional economic integration, and national connectivity. In this context, national road development plays a strategic role as an integrated development model that combines industrial efficiency, sustainable spatial planning, and transportation technology innovation. In 2020, the length of national roads in East Kalimantan Province was recorded at around 1,710.90 km, while provincial roads reached 884.80 km and regency/city roads reached 10,735.25 km. The four main research routes that cross East Kalimantan to West Kalimantan range in length from 705 to 1,668 km, covering national, provincial, district, and city sections. This infrastructure is not only a means of mobility, but also a physical framework that unites various centers of economic activity, industrial estates, and strategic development areas such as the Maloy Batuta Special Economic Zone (SEZ) and the Derawan National Tourism Strategic Area (KSPN). Conceptually, the national road project in Kalimantan shows how infrastructure policy can serve as a catalyst for the integration of planning and industrial disciplines, by linking spatial, economic, and technical aspects in a single sustainable development system. In terms of industrial management, the construction of national roads in Kalimantan requires efficient planning in the supply chain of materials, labor, and implementation time. This kind of project requires an integrated project management system that is able to manage the logistics of materials from different regions, given that most construction materials have to be transported across provinces with challenging geographical conditions. The project-based industrial management approach is applied to ensure the availability of resources on time and in the right quantity, as well as reduce cost wastage due to delays or distribution disruptions. In addition, the involvement of local industries in the provision of materials and labor is part of the strategy of increasing regional economic capacity—a form of synergy between industrial efficiency and regional empowerment. From the perspective of regional planning, the construction of national roads in Kalimantan is a strategic instrument in the formation of an integrated island spatial structure. Prior to this project, most areas of Kalimantan still had limited access, especially in the interior and border areas. By connecting East, Central, West, South, and North Kalimantan through the Trans-Kalimantan network, a new economic corridor is formed that strengthens inter-regional interactions and balances growth between coastal and inland areas. National roads also function as a support for the development of industrial and agricultural estates such as food estates in Central Kalimantan, border areas in North Kalimantan, and energy industrial estates in East Kalimantan. Transportation is not just a physical infrastructure, but also a spatial planning instrument that changes the economic structure and distribution of population activities. Meanwhile, the discipline of transportation engineering plays a vital role in designing a system that suits the geographical and ecological conditions of Kalimantan. Many of the region's national roads pass through swamps, large rivers, and tropical forest areas that are sensitive to environmental changes. Therefore, an adaptive engineering approach is a must, such as the application of flood-resistant road design, elevation on inundation-prone sections, and the use of pavement technology that is suitable for peatland conditions. Another challenge is interprovincial connectivity that must take into account long-term traffic capacity, especially with the increase in economic activity due to the development of the capital city and the development of industrial estates.

East Kalimantan, as the center of Indonesia's new growth, is an ideal case study for an integrated development approach. The government targets an increase in the level of road stability from 69.77% in 2020 to 90% in 2024, in line with the increase in the ratio of road length to area which is still below the national average. This effort requires simultaneous planning between ministries and local governments, as well as synergy between the industrial, transportation, and spatial planning sectors. National road projects are also directed to support connectivity to the IKN, ensuring logistics flows, population mobility, and distribution of strategic commodities such as mining products, palm oil, and processing industry products.

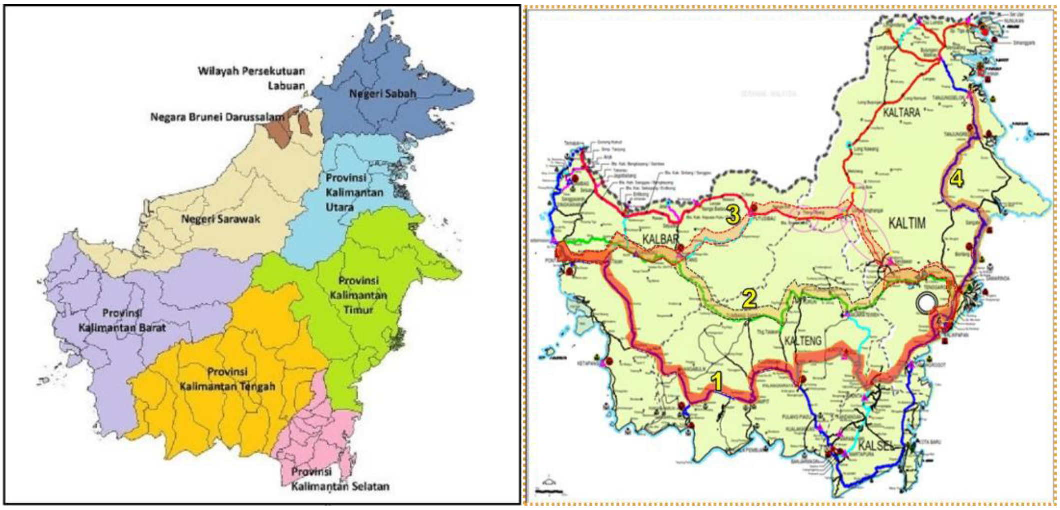

Figure 13.1. Map of Kalimantan and Route Location

Institutionally, an integrated approach can be seen from cross-sector coordination between the Ministry of Public Works and Housing, Bappenas, and the provincial government. This approach reflects the principle of integrated infrastructure governance, where road planning is not carried out separately, but is aligned with the regional spatial plan (RTRW), national transportation master plan, and industrial estate development strategy. The construction of national roads serves a dual purpose: as a physical investment to facilitate mobility, and as a policy instrument to encourage the structural transformation of the region. In terms of economic benefits, national road projects in Kalimantan accelerate the formation of regional value chains. Industrial estates in Balikpapan, Samarinda, and Bontang benefited through logistics efficiency and increased product competitiveness. On the other hand, previously isolated rural areas are starting to connect with public markets and facilities, creating significant social impacts in the form of increased access to education, health, and employment. Conceptually, this shows the successful integration of economic and social goals within the framework of integrated transport development. However, sustainability challenges also arise. Some Trans-Kalimantan roads are still prone to flooding and damage due to high rainfall. In this context, collaboration between transportation engineering and environmental planning is essential to ensure the resilience of infrastructure without compromising the balance of the ecosystem. In addition, industrial management plays a role in designing efficient road maintenance systems through performance-based maintenance contracts and sensor-based monitoring technology to extend the life of the road. Overall, the construction of national roads in Kalimantan can be seen as a real laboratory for interdisciplinary approaches. The project shows that the success of infrastructure development depends not only on technical or funding aspects, but also on systemic integration between industrial efficiency, spatial planning policy, and transportation engineering innovation. On this basis, Kalimantan is not only a region with increased physical connectivity, but also a symbol of transformation towards smart, competitive, and sustainable regional development.

A study [16] confirms that the success of transport corridor construction in Europe depends on alignment between spatial planning policies and national infrastructure planning oriented towards sustainability and social inclusion. National road construction serves a dual function: as a physical investment that facilitates mobility and as a policy instrument that encourages the structural transformation of the region. In the economic context, this is in line with the findings of [17] who outlined that sustainable road construction must take into account inter-sector integration, where social, economic, and environmental dimensions are intertwined in systemic infrastructure planning. In Kalimantan, the Trans-Kalimantan national road project is accelerating the formation of a regional value chain. Industrial estates such as Balikpapan, Samarinda, and Bontang gained significant logistics efficiency, strengthening the competitiveness of regional products. This is consistent with the findings of [18] who reviewed integrated railway–highway (IRH) designs and found that intermodal and land-use integration reduce transportation investment costs by up to 30% and accelerates the growth of new industrial estates. The social impact of national road development is also very real. Previously isolated hinterland areas are now connected to markets, educational centers and public facilities. [19] study on the East African corridor shows that integrated transport connectivity can reduce access inequality by up to 25% through improved logistics efficiency and the implementation of green logistics in hinterland regions. However, sustainability challenges also arise, especially on roads that are prone to flooding and erosion. Collaboration between transportation engineering and environmental planning is essential to ensure the durability of infrastructure. [20] highlight the importance of dynamic risk management systems for public-private partnership (PPP) based highway projects, emphasizing the importance of stock and flow simulations to anticipate extreme environmental impacts. In terms of industrial management, the performance-based maintenance contract approach is increasingly applied. This model has proven to be efficient in reducing maintenance costs throughout the project lifecycle. The study of [21] developed a performance-based road maintenance model in West Lombok that reduces life cycle costs by up to 35% and increases public transparency through multi-stakeholder governance. In terms of governance, the integration of policies across sectors and levels of government is key. [22] through a revised study of the Piedmont Regional Plan (Italy) affirmed that the successful implementation of infrastructure development depends on the synergy of multi-level governance between the central, regional, and private governments. Meanwhile, [23] show that the success of the Madrid Nuevo Norte megaproject in Spain is greatly influenced by strategic coordination between planners, developers, and communities within the framework of public-private partnerships. From a strategic planning perspective, the integrated infrastructure governance model also emphasizes coordination between sectors on a regional scale. [16] and [17] both show that road infrastructure connected to spatial planning and industrial policies can be a catalyst for economic transformation, as long as it is followed by mechanisms of supervision and public participation. The construction of national roads in Kalimantan can be seen as a real laboratory for an interdisciplinary approach. This project shows that the success of infrastructure development does not only depend on technical aspects or funding, but also on systemic integration between industrial efficiency, spatial planning policies, engineering innovation, and collaborative governance. On this basis, Kalimantan is not only a region with increased physical connectivity, but also a symbol of transformation towards smart, resilient, and sustainable regional development.

13.3. Holistic Evaluation: Social, Economic, and Environmental Impacts

The evaluation of national road construction in Kalimantan needs to be carried out holistically because this project not only produces physical infrastructure, but also triggers structural changes in the social, economic, and environmental order. This integrated evaluation approach places communities, regions, and ecosystems as a single system that interacts with each other. By looking at these three dimensions together, a development policy can be judged not only by its technical success, but also by the extent to which it supports social well-being, economic efficiency, and long-term ecological sustainability. Socially, the construction of national roads in Kalimantan has a significant impact on people's lifestyles, especially in areas that were previously isolated. Increased accessibility opens up opportunities for population mobility, expanding access to education, health services, and the job market. Areas in the interior that were previously difficult to reach are now starting to connect with city centers and public facilities, thus accelerating the process of social and economic integration. In East Kalimantan, for example, improved inter-district connectivity supports the growth of the Nusantara Capital City (IKN) buffer areas such as Kutai Kartanegara and North Penajam Paser, which are beginning to experience new urbanization and increased economic activity of local communities. However, social change also brings challenges. Increasing migration flows to new areas can cause pressure on land, housing, and potential social conflicts due to differences in spatial use interests. In this context, social management approaches and participatory planning are important so that infrastructure development does not create new inequalities. It is important to realize that local communities, including indigenous communities and rural dwellers, have a strong attachment to their living spaces. Therefore, the public consultation process and community involvement in road planning and maintenance are key aspects in maintaining social sustainability. From the economic side, the impact of national road construction is very felt in improving the efficiency of logistics and distribution of goods. Before development, the cost of interprovincial transportation in Kalimantan was relatively high due to the condition of damaged roads and limited bridges. With the existence of stable national roads, logistics costs decrease, travel time between regions decreases, and the capacity of goods flows increases. This condition encourages the formation of new economic corridors along the Trans-Kalimantan route that connects industrial, agricultural, and trade areas. In addition to distribution efficiency, road construction also opens up investment opportunities in supporting sectors such as logistics services, construction, trade, and tourism. The Maloy Batuta Special Economic Zone (SEZ) in East Kalimantan, for example, benefits from increased accessibility to ports and industrial centers, which in turn increases regional competitiveness. For the community, improving transportation infrastructure also has a direct impact on income, as it opens up access to new markets and economic sources. However, economic evaluations highlight not only growth, but also sustainability and equitable distribution of benefits. Without careful spatial planning, increased access can lead to economic concentration at only a few points, while remaining lagging behind. Therefore, road development policies must be accompanied by regional economic development strategies, such as strengthening local industrial clusters, empowering small and medium enterprises (SMEs), and increasing the capacity of local workers so that the benefits of development are spread evenly.

This perspective is in line with the Holistic Impact Measurement (HIM) model developed [24], which assesses transportation sustainability based on the integration of economic, social, and environmental dimensions in one equivalent quantitative framework. Socially, the construction of national roads has a transformational impact on the lives of local communities, especially in previously isolated areas. Increased accessibility opens up mobility opportunities, expands access to education and health, and accelerates socio-economic integration between regions. These findings are in line with the research of [25] which emphasizes that sustainable planned road access increases can improve people's welfare without sacrificing biodiversity and quality of life. However, these social changes also present new challenges, such as migration and pressure on land resources. A participatory approach is crucial so that local communities, including indigenous communities, are not marginalized. In this regard, [26] emphasize the importance of dynamic performance management in managing public resources and building governance models that are responsive to social change. From an economic perspective, the construction of national roads has a significant impact on logistics efficiency and equitable distribution of regional growth. Prior to this project, the cost of interprovincial transportation in Kalimantan was very high due to the limitations of basic infrastructure. Now, with a more robust road network, logistics costs are decreasing and the flow of goods is increasing. The study of [27] confirms that the implementation of Life Cycle Sustainability Assessment (LCSA) in road projects allows for a comprehensive assessment of economic efficiency, social value, and environmental impact throughout the project life cycle. This positive economic impact can also be seen in the formation of new economic corridors along Trans-Kalimantan. Areas such as Balikpapan, Samarinda, and Bontang are now efficiently connected to logistics centers and ports, in line with the findings of [28] showing that Disaster Risk Reduction Audits (DRRAs) and data-driven approaches are able to increase the economic resilience of infrastructure to climate and disaster risks. In addition, increased connectivity also strengthens the competitiveness of local investment and productivity, as explained [29] in their systematic review of highway project management that highlights the importance of multi-stakeholder coordination, digitalization, and budget transparency to drive the growth of the national construction industry. From an environmental perspective, road construction poses potential pressure on forest and peatland ecosystems. Therefore, a green infrastructure-based mitigation approach is needed. According to [30], a holistic evaluation method of road maintenance that takes into account the impacts of emissions, biodiversity, and public health is an important step towards sustainable infrastructure policies. Furthermore, [31] in a study of international sustainability rating systems (SRSs) found that the proportion of global road project assessments is still inclined towards environmental (43%) and social (42%) aspects, while the economic dimension is only 15%, indicating the need for rebalancing in national road planning to be more comprehensive. A holistic evaluation of national road projects in Kalimantan must thus assess the dynamic relationship between economic growth, social welfare, and environmental carrying capacity. The integration of systems thinking approaches as recommended [24] and [25] can help policymakers design infrastructure strategies that are inclusive and adaptive to climate change, technology, and community needs.

Ecologically, the construction of national roads in Kalimantan has consequences that need to be managed carefully. The island of Borneo is known for its tropical forest ecosystem that is rich in biodiversity. The construction of roads that pass-through forests, swamps, or large rivers can cause habitat fragmentation, disturbances to the hydrological system, and the potential for increased deforestation if not balanced with strict regulations and environmental monitoring. Therefore, the principle of green infrastructure needs to be applied in every stage of development, starting from road route planning, material selection, to construction techniques with minimal ecological impact. Some of the mitigation measures that can be implemented include the construction of wildlife bridges, road elevations in flood-prone areas, and the use of sustainable drainage systems that maintain groundwater balance. In addition, the use of environmentally friendly pavement technology and local materials can reduce the carbon footprint of construction. In the context of Kalimantan, which has vast peatlands, soil stability and carbon emissions are important issues that demand innovation in transportation techniques as well as data-driven environmental risk management. It is also important to note that environmental impacts occur not only during construction, but also during the operational phase. Increased vehicle activity can increase exhaust gas emissions and noise, especially in residential areas. For this reason, sustainable transportation systems such as electric vehicles, intelligent traffic management, and sensor-based road maintenance can be a long-term solution. Synergy between regional planning and transportation techniques is needed so that road construction not only expands mobility networks, but also supports the transition to low-carbon transportation systems.

The green infrastructure approach is key in designing a road network that is not only functional but also environmentally friendly, for example through the implementation of wildlife corridors to maintain the connectivity of terrestrial and aquatic ecosystems [32]. In tropical regions such as Borneo, the involvement of spatial data-driven technologies in ecological risk mapping has proven effective in identifying areas of high conservation value, as demonstrated by a study in the Greater Serengeti that blends ecological and socio-economic analyses to design sustainable pathways [33]. Furthermore, road construction in forest and peat areas needs to consider soil stability and carbon emissions generated from construction activities. The study [34] emphasizes that infrastructure in the Amazon forest region faces similar challenges in maintaining hydrological balance and preventing soil erosion through the application of sponge city design principles and the use of porous materials. This principle can be adapted for Kalimantan, especially in peatland and swampy areas that are prone to seasonal flooding. In addition, the results of [35] research show that the development of transportation infrastructure such as standard gauge railways in Kenya leads to a 15% reduction in forest and farmland cover, thus confirming the importance of GIS-based environmental monitoring systems and remote sensing during the project life cycle. To maintain ecological carrying capacity, green infrastructure governance strategies must include the implementation of sustainable drainage systems (SuDS), the use of low-emission local materials, and road designs that pay attention to natural water flow and soil structure. Such practices have been widely applied in sustainable urban development policies in India and Latin America, emphasizing the integration between spatial planning and the protection of natural landscapes [36] ; [37]. At the same time, it is important to pay attention to the socio-ecological aspect, i.e. the involvement of local communities in environmental surveillance and infrastructure maintenance, as suggested [38] in a study on sustainable infrastructure development in Nepal. Kalimantan's highly diverse ecosystem context demands cross-disciplinary policies that link industrial management, regional planning, and transportation techniques within a single integrated environmental governance framework. This approach is in line with the view of the integrated climate-biodiversity framework, which emphasizes that transportation infrastructure should be part of the global climate change mitigation and biodiversity protection strategy [32]. Thus, the application of the principle of green and resilient infrastructure is not only a technical responsibility, but also a policy commitment to ensure that the construction of national roads in Kalimantan goes hand in hand with the conservation of the ecosystem and the welfare of the surrounding community. A holistic evaluation approach demands synergy between social, economic, and environmental engineering disciplines. Industrial management plays a role in ensuring that projects are run efficiently and sustainably, including in the operation and maintenance phases. Regional planning provides guidance so that the infrastructure is suitable for the spatial layout and carrying capacity of the environment, while transportation techniques ensure that the physical system of roads can withstand the extreme geographical conditions of Kalimantan. This cross-faceted evaluation needs to be carried out on an ongoing basis so that the project is not only successful at the development stage, but also provides long-term benefits to the community and the environment. In the long run, the success of national road projects in Kalimantan will be measured not only by the length of the roads built, but by how much they contribute to improving people's welfare, regional economic growth, and environmental conservation. This kind of integrative approach ensures that infrastructure development is not an ecological burden, but an instrument to strengthen Kalimantan's social and economic resilience in the future.

13.4. Future Recommendations

The construction of national roads in Kalimantan provides many important lessons on how large-scale infrastructure projects should be planned and implemented in an integrated manner. This experience can be the basis for formulating recommendations for similar projects in the future, both in Kalimantan and other regions in Indonesia that have diverse geographical and socio-economic characteristics. An approach that integrates aspects of industrial management, regional planning, and transportation techniques has proven to be able to increase development effectiveness, but also requires strengthening inter-agency coordination, adaptive project governance, and sustainable innovation. The first recommendation is the need to strengthen the inter-disciplinary integration mechanism from the early stages of planning. In large infrastructure projects, often each discipline works separately: spatial planners focus on land use, transportation engineers on the technical aspects of roads, and project managers on cost efficiency. In fact, project effectiveness can only be achieved if all of these approaches are synergized in one integrated strategy framework. Therefore, a permanent coordination forum is needed between central agencies (such as the Ministry of Public Works and Housing, Bappenas, and the Ministry of Transportation) and local governments and the private sector. This forum serves as a forum for policy integration, synchronization of spatial plans, and harmonization of technical and budget standards. In addition, the project governance system needs to be equipped with an integrated project delivery (IPD) instrument, which combines the planning, implementation, and supervision processes in one collaborative system. This approach encourages collaboration between professions from the conceptual phase, reduces the potential for duplication of activities, and improves the efficiency of resource use. Thus, the development of future infrastructure is not only a technical matter, but also the result of synergies across sectors that complement each other. Technological advances provide great opportunities for the efficiency and sustainability of infrastructure projects. In future road projects, the implementation of smart construction management and intelligent transportation systems (ITS) needs to become the new standard. The project digitization system allows for data-driven planning, real-time progress monitoring, and more accurate risk analysis. The use of Building Information Modeling (BIM), for example, can help integrate engineering design, work schedules, and budgeting in one digital platform, thereby minimizing the potential for errors and waste. In terms of transportation engineering, technologies such as road sensors, automated traffic monitoring systems, and performance-based maintenance management will extend the life of infrastructure and lower long-term operational costs. In tropical regions such as Kalimantan, this technology is also important for early detection of damage due to floods or soil movements. Meanwhile, in the context of industrial management, the use of digital supply chain information systems can increase the transparency and efficiency of construction material distribution, especially in cross-provincial projects with complex geographical conditions.

This approach is strengthened by a study by Ping Li et al. (2023) that affirmed the effectiveness of cloud-edge integration-based architecture systems in China's high-speed rail projects in managing data and coordination between stakeholders in real time [39]. Inter-disciplinary integration at the planning stage is a key recommendation so that all stakeholders—spatial planners, transportation engineers, and project managers—are in one unified strategic framework. A study [40] shows that the integration of Building Information Modeling (BIM) with Geographic Information System (GIS) (through the 4D and 5D BIM approach) improves spatial coordination and efficiency of road infrastructure planning. Thus, a coordination system like this is very relevant to be applied in the context of Indonesia, which has high geographical and regulatory complexity. Advances in digital technology open up great opportunities for the implementation of smart construction management and intelligent transportation systems (ITS). [41] study confirms that the use of BIM in construction project planning allows simultaneous control of design, schedule, and cost, reducing the risk of delays and wastage. This approach can be strengthened by the AI-driven Digital Twin concept, as described [42], which enables dynamic simulation of infrastructure and construction logistics conditions, including predictions of road damage due to flooding or overload. In the context of industrial management, the supply chain system of digital integration also plays an important role in material and labor efficiency. [43] show that the application of smart contracts and Robotic Process Automation (RPA) in modular construction supply chains can increase transparency and speed up the project reporting process. Such integration is particularly relevant for cross-provincial projects in Kalimantan that face coordination challenges and long logistical distances. In terms of transportation engineering, the use of road sensors and performance-based maintenance systems is an important step to extend the life of infrastructure. The findings of [44] show that the application of Internet of Things (IoT) technology and AI-based monitoring in transportation projects can reduce maintenance costs by up to 20% and improve the energy efficiency of highway vehicles. The integration between BIM, IoT, and predictive analytics can be a model for national road management that is adaptive to climate risks and land level change. For tropical regions such as Kalimantan, digital twin-based technology and geotechnical sensors can detect potential landslides and floods early, so that maintenance systems can be carried out proactively. This approach is in line with the concept of intelligent high-speed transport infrastructure which emphasizes monitoring the condition of the transportation network in a continuous and data-driven manner [39]. In addition, [45] emphasized the importance of using BIM in the construction of prefabricated infrastructure to speed up construction time and reduce the environmental impact of projects. Finally, for this synergy to be effective nationally, institutions that are able to regulate integration across ministries and the private sector are needed. Systems such as IoT-based Intelligent Construction Systems, as developed [46], can be used as models for creating a "construction information network" that connects government, contractors, and project owners in a transparent and efficient manner.

The success of the national road project in Kalimantan shows the importance of striking a balance between physical development and environmental sustainability. Therefore, future projects must adopt the principle of green infrastructure as a basic paradigm. The development plan needs to be accompanied by an analysis of the carrying capacity and environmental capacity that is integrated in the feasibility study, not just an administrative annex. Road construction in sensitive areas such as peatlands, swamps, or tropical forests requires adaptive construction techniques, such as the use of geotextiles, layered drainage systems, and long bridge structures to maintain water circulation. In addition, it is necessary to develop ecological compensation policies such as reforestation, the creation of animal corridors, and the management of green spaces along road corridors. Environmental surveillance based on satellite and drone technology can be used to ensure that development runs according to the principles of sustainability and does not cause ecosystem degradation. Sustainable infrastructure development not only emphasizes technical and economic aspects, but also the welfare of the surrounding communities. Therefore, every large project needs to be accompanied by a strategy to empower local communities, both in the form of labor involvement, support for micro and small enterprises, and skills training that is relevant to the needs of the project. This approach not only creates short-term economic effects, but also builds the social and economic capacity of the community to adapt to the changes brought by development. The public consultation process should also be an integral part of project planning. Local communities, including indigenous communities, need to be involved from the early stages so that local aspirations and wisdom can be accommodated. Thus, the project is not only socially accepted, but also reinforces the community's sense of belonging to the infrastructure being built. In the context of Kalimantan, this is important because the ethnic diversity and social structure of the community require an inclusive and culturally sensitive approach to development. Future road construction should be seen as part of the regional development system, not as a stand-alone project. Roads are an instrument of driving economic growth, so infrastructure development plans must be in line with the regional spatial plan (RTRW) and regional medium-term development plan (RPJMD). In developing regions such as Kalimantan, road connectivity should be directed to strengthen industrial clusters, agricultural centers, and strategic economic zones such as SEZs and KSPN. Integration between infrastructure and regional economic planning can also accelerate equitable development. For example, the construction of connecting roads between industrial estates can be accompanied by the construction of integrated logistics facilities, freight terminals, and multimodal access to ports or airports. This approach will shorten the distribution chain, lower logistics costs, and increase regional competitiveness.

The application of this principle is in line with the concept of Nature-based Solutions (NbS) which emphasizes the integration of ecological, social, and economic functions in regional management [47]. In the context of fragile ecosystems such as Borneo's peatlands and swamps, adaptive construction techniques such as the use of geotextiles, layered drainage systems, and long bridge structures are required to maintain hydrological balance and reduce the risk of land subsidence. A study [48] confirms the importance of hydrological mitigation strategies in construction projects on peatlands to maintain soil stability and prevent degradation of wet habitats. In addition to technical mitigation, socio-ecological approaches also need to be strengthened. The experience of peatland restoration in Central Kalimantan shows that the success of ecosystem restoration is highly influenced by collaboration between local communities, government agencies, and the private sector in the planning and monitoring process [49]. The involvement of indigenous peoples from the early stages of planning helps ensure that the project is not only socially accepted, but also strengthens the relationship between people and the environment. On the other hand, [50] highlight that the exploitation of natural resources in peatlands without strong regulation can lead to permanent habitat loss, so surveillance based on satellite and drone technology is essential to prevent ecological degradation. Ecological compensation policies such as reforestation and the development of wildlife corridors are also important elements in maintaining ecological balance around road corridors. The study [51] confirms that low-carbon infrastructure policies must be accompanied by biodiversity protection to avoid conflicts between climate mitigation goals and habitat conservation. In practice, the development of green spaces along roadways as well as the use of local vegetation can help stabilize the soil and reduce erosion, as applied in ecosystem-based restoration approaches in China [47]. However, the sustainability of infrastructure development does not only depend on technical aspects, but also on the empowerment of local communities. Studies on community-based ecosystem restoration show that the involvement of local labor in peat forest rehabilitation activities increases social ownership and the effectiveness of environmental management [49]. In Kalimantan, a similar strategy can be implemented through training and support programs for small businesses in the construction and road maintenance sectors. Finally, the construction of national roads in the future must be seen as part of a regional development system that is integrated with spatial planning and regional economic strategies. This is in line with the ecosystem-based special economic zones (SPEZ) approach designed to combine spatial planning, economics, and environmental conservation in one integrated policy framework [52]. Integration between infrastructure and economic planning like this allows for the establishment of an efficient logistics network that not only strengthens connectivity between regions, but also maintains the carrying capacity of the environment and the social welfare of the surrounding communities.

The last recommendation is the need for a system of evaluation and continuous learning. Every big project must leave a legacy of knowledge that can be a reference for subsequent projects. Evaluations are carried out not only at the end of the project, but also periodically during the construction and operational phases. The results of the evaluation must be well documented in the form of performance reports, case studies, and technical guidance so that they can be used to improve the planning system and the implementation of other national projects. The national road construction project in Kalimantan proves that the integration of disciplines can result in more effective, efficient, and sustainable development. For similar projects in the future, success is determined not only by the length of the road built or the value of the investment absorbed, but by the extent to which the project is able to strengthen the economic integration of the region, improve the quality of life of the community, and maintain the balance of the environment. Through the synergy between industrial management, regional planning, and transportation engineering, Indonesia can realize a smarter, more inclusive, and future-oriented infrastructure development model.

The construction of national roads in Kalimantan is a tangible reflection of how inter-disciplinary integration can change the development approach from just a physical activity to a sustainable regional transformation strategy. Through the synergy between industrial management, regional planning, and transportation engineering, infrastructure projects not only generate connectivity between regions, but also strengthen economic structures, improve social welfare, and maintain ecological balance. Kalimantan's experience shows that the success of development is highly determined by the ability of various sectors to work in a coordinated, adaptive, and long-term oriented manner. In terms of industrial management, supply chain efficiency, project management, and resource optimization are important factors in reducing costs and accelerating job completion. In the realm of regional planning, road construction should be seen as an integral part of the spatial structure, not just a transportation route, so that each road section can promote local economic growth while strengthening regional integration. Meanwhile, transportation techniques play a role in ensuring the quality and resilience of infrastructure to challenging geographical and climatic conditions, such as those encountered in Kalimantan. These three areas, when combined in one systematic framework, result in more efficient, targeted, and far-reaching development.

Socially, the national road project has opened up access for rural communities to enjoy public services and new economic opportunities. Economically, this infrastructure accelerates the flow of goods and services and connects industrial estates with ports and logistics centers. However, development also poses environmental challenges that need to be managed through the principles of green infrastructure and the application of sustainable construction technology. A thorough evaluation of social, economic, and ecological aspects must be an integral part of every stage of development, so that the benefits of the project can be felt fairly and sustainably. In the future, similar projects in other regions need to learn from Kalimantan's experience: the importance of cross-agency coordination, the use of smart technologies, the empowerment of local communities, and the integration between infrastructure policies and regional spatial planning. By applying the principle of integration of disciplines, every development project will not only produce roads that connect places, but also connect potential, knowledge, and people in one vision of equitable national development. CHAPTER 13 emphasizes that integrated development is not only a technical strategy, but a new paradigm in national development planning and implementation. Only by combining the power of science, technology, and social collaboration, Indonesia can realize infrastructure development that not only builds space, but also builds civilization.

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CHAPTER 14

CONCLUSIONS AND RECOMMENDATIONS

The development of the National Road Network in Kalimantan is a tangible representation of Indonesia's efforts to build a solid, inclusive, and sustainable connectivity foundation in the midst of the dynamics of national transformation towards the era of the IKN of the archipelago. The project serves not only as a physical infrastructure connecting regions, but also as a strategic instrument that triggers multidimensional change—covering economic, social, ecological, governance, and geopolitical aspects. In the process, road construction in Kalimantan shows how the interaction between public policy, engineering, industrial innovation, and community participation can form a new face of national development that is more adaptive to the challenges of the times. This chapter is structured to summarize the overall findings, discussion, and analysis of the previous chapters in four main subsections. First, the Main Conclusion of Each Chapter, which summarizes the core ideas and results of thought in each discussion topic. Second, the Recommendations for Sustainable Infrastructure Development, which highlight strategies and technical and policy approaches in maintaining a balance between economic progress and environmental sustainability. Third, Suggestions for Advanced Research, which focuses on the development of science, technology, and methodologies in supporting future development innovations. Fourth, a message to Stakeholders: Government, Industry, and Society, which emphasizes the importance of cross-sectoral collaboration as the key to the success of national development. Through the preparation of Chapter 14, it is hoped that a comprehensive picture of the direction, achievements, and challenges of the development of the national road network in Kalimantan will be obtained. More than that, this chapter is an academic reflection as well as a strategic recommendation for all stakeholders so that infrastructure development in Indonesia can continue to develop towards a new paradigm—development that not only pursues economic growth, but also strengthens social justice, regional independence, and environmental sustainability.

14.1. Key Conclusions of Each Chapter

The construction of the National Road Network in Kalimantan is a concrete manifestation of the national development strategy that aims to strengthen connectivity between regions, reduce logistics costs, and encourage economic equity in regions that have been left behind. Through the discussion that stretches from Chapter 1 to Chapter 13, it can be concluded that this infrastructure project is not just a physical construction activity, but a multidimensional intervention that includes technical, economic, social, environmental, and governance aspects. Each chapter presents a different, but interconnected dimension in forming a sustainable development framework for Kalimantan and Indonesia in general. Chapter 1 outlines the basic context of the development of the national road network in Kalimantan as part of Indonesia's strategic transformation, especially in supporting the development of the IKN of the archipelago. National roads are positioned as the backbone of interprovincial connectivity that plays an important role in integrating production, distribution, and consumption centers throughout the island region. While increased accessibility has driven local economic growth and expanded access to public services, the benefits have not been evenly distributed. Coastal areas benefit more than inland areas, which still experience isolation and limited infrastructure. This phenomenon creates a development paradox, where natural resources are intensively exploited but the benefits have not yet fully returned to the local community. Chapter 2 expands the perspective by asserting that road construction should be understood as a multidimensional process that includes interactions between economic, social, ecological, and geopolitical interactions. Kalimantan's extreme geographical conditions—with peatlands, steep hills, and complex river systems—are a major challenge in infrastructure development. However, the existence of an improved road network has had a positive impact in the form of increasing logistics efficiency and strengthening the supply chain of agribusiness and extractive industries. On the other hand, unplanned development risks deforestation and environmental degradation. Therefore, a spatial approach and inclusive public policies are needed so that development does not widen the gap between regions. Chapter 3 discusses the aspects of industrial management and project management that are the backbone of the success of infrastructure development in Kalimantan. In challenging geographical contexts, the application of planning methods such as the CPM and PERT is proving essential to optimize project time and costs. Digital technologies such as BIM are becoming strategic tools for cross-disciplinary integration, reducing the risk of design errors, and improving the efficiency of project implementation. In addition, the analysis of the trade-offs between time, cost, and quality is becoming an integral part of modern project management oriented towards sustainability and work safety.

Chapter 4 highlights the technical evaluation of the condition of national road pavements in Kalimantan. Through indicators such as the PCI and the IRI, it is known that road conditions in this region face typical challenges due to low soil carrying capacity, high rainfall, and heavy traffic pressure from mining and plantation vehicles. Engineering solutions such as the use of geosynthetics, soil stabilization with industrial waste, and sustainable drainage systems are the innovations needed to improve the service life of the road. In addition to the technical aspects, the evaluation also highlighted the importance of data-driven preventive maintenance policies that can reduce the overall road lifecycle costs. Chapter 5 and Chapter 6 emphasize the role of public policy in the management of national infrastructure. Effective road construction does not only depend on technological sophistication, but also on policy directions that favor equity and sustainability. The government is required to implement evidence-based policy making that relies on technical data such as VCR and average travel speed to assess traffic performance. This approach ensures that the decisions taken are objective, transparent, and adaptive to field conditions. In addition, synergy between regulatory policies, technical aspects, and public participation is key to realizing an efficient and inclusive transportation system. Chapter 7 places emphasis on the basic principles of road and bridge engineering as part of resilient infrastructure development. Each project must begin with an accurate analysis of field needs and conditions, including soil carrying capacity, traffic volume, and topographic conditions. The application of geometric design and proper drainage systems is a determining factor for the life of infrastructure services. A case study of the repair of the Kapuas 1 Bridge in Pontianak shows that infrastructure modernization can be carried out efficiently without completely replacing the structure, but rather through an adaptive rehabilitation approach. The integration between environmental engineering and engineering is the foundation of the future of transportation development in Indonesia. Chapter 8 outlines the logical framework for sustainable infrastructure development that focuses on mitigating environmental impacts and applying environmentally friendly technologies. Technologies such as MBR, WTE, GIS, and IoT sensors are used to improve energy efficiency and reduce negative impacts on ecosystems. This approach places environmental engineering as a strategic element in maintaining a balance between development and nature conservation.

Chapter 9 highlights the close relationship between transportation engineering and national mobility systems. LOS analysis, traffic flow management, and the application of ITS are the basis for improving transportation efficiency in archipelagic areas such as Kalimantan. Good road infrastructure has proven to be a catalyst for rural economic growth, especially in strengthening agricultural supply chains. Thus, transportation is not only a means of mobility, but also an instrument of socio-economic development. Chapter 10 links infrastructure development with the agricultural sector. National roads and production roads are important elements in supporting the farming system and smoothing the flow of goods from villages to markets. Agricultural infrastructure integrated with modern logistics systems is able to increase productivity, reduce post-harvest losses, and open up opportunities for export-oriented agribusiness. However, this success requires good and sustainable governance so as not to cause new inequality or degradation of natural resources. Chapter 11 discusses the role of environmental technology in realizing green development and a circular economy. The application of renewable energy, the use of bio-based materials, and a decentralized waste management system are strategic steps to reduce emissions and resource efficiency. The IKN project is an example of the comprehensive application of green technology, including the integration of low-emission transportation systems and the concept of smart cities. The main challenges still lie in the aspects of financing, technical capacity, and institutional coordination, but great opportunities are opening up through cross-sectoral partnerships and strengthening local technology research. Chapter 12 focuses on the analysis on VOC and Value of Time as indicators of transportation system efficiency. Good road conditions have been proven to significantly lower the BOK and increase travel productivity, which ultimately has a positive impact on the economic growth of the region. A data-driven approach in transportation policy formulation is a must so that infrastructure investment provides optimal socio-economic benefits for the community. Chapter 13 is a synthesis of the entire discussion, emphasizing the importance of cross-disciplinary integration in national infrastructure development. Industrial management, regional planning, and transportation engineering must run within one mutually reinforcing strategic framework. The construction of national roads in Kalimantan is not only about connecting locations, but also connecting potential, knowledge, and communities. With cross-sectoral collaboration, the application of smart technologies, and the strengthening of spatial justice-based policies, development can be an instrument for regional transformation towards environmental prosperity and sustainability. The conclusion of the entire chapter shows that the success of the development of the national road network in Kalimantan depends on Indonesia's ability to integrate the technical, social, economic, and ecological dimensions into a single adaptive and sustainable governance system. Roads are not just a means of mobility, but a strategic medium that connects the future of nation development with the values of sustainability and social justice.

14.2. Recommendations for Sustainable Infrastructure Development

The development of the national road network in Kalimantan, with all its geographical, social, and ecological complexities, demands a new paradigm in infrastructure planning and implementation. Sectoral and short-term approaches must be replaced by integrated strategies based on data, technology, and environmental sustainability. The following recommendations are compiled based on the main findings of each previous chapter and are directed to strengthen the effectiveness, efficiency, and sustainability of national road construction in Kalimantan and other regions in Indonesia. First, infrastructure development must be based on the concept of green infrastructure that balances technical, social, and ecological aspects. In the context of Kalimantan, where peatlands and tropical forests predominate, this approach is crucial to prevent ecosystem degradation. The use of technologies such as geofoam, porous pavement, vegetative bioengineering, and ecoducts (animal bridges) needs to be made a national standard in the design of road projects. Sustainability principles must be applied from the planning stage, including through the implementation of a participatory EIA and the integration of spatial data based on GIS. In addition, projects must utilize eco-friendly construction materials such as recycled asphalt, stabilized industrial waste, and bio-based materials to reduce carbon emissions and reduce dependence on non-renewable resources. Second, the government needs to strengthen a data-based road asset management system as a foundation in maintaining the quality and lifespan of infrastructure services. Currently, most road maintenance policies are still oriented towards reactive (after damage maintenance), not preventive. A data-driven approach through the integration of PCI, IRI indicators, and real-time traffic data will allow for more accurate rehabilitation prioritization. This system can be integrated in a national digital platform that uses IoT technology for predictive monitoring of road conditions. With such a system, budget allocation can be more efficient, transparent, and accountable, while increasing infrastructure resilience to climate risks and overload. Third, the development of road infrastructure in Kalimantan must be supported by integrated spatial planning that combines economic development with the protection of the local environment and culture. The RTRW needs to be aligned with the national road network plan so that each transportation corridor can be a driver of regional economic growth, not just a path for goods mobility. Local governments must play an active role in ensuring that road construction supports the development of new growth centers in the interior, so that the gap between coastal and upstream can be reduced. In this context, the development of green economy corridors connecting industrial estates, ports, and agricultural production centers need to be a national priority. Fourth, the application of digital technology and engineering innovation must be the main pillars of sustainable road development. The integration of BIM, digital twins, and sensor-based monitoring systems can improve project efficiency while minimizing the risk of design errors and construction delays. The technology also supports cross-disciplinary collaboration between engineers, regional planners, and environmentalists. In addition, the adoption of ITS can strengthen traffic efficiency and road safety. The use of automatic speed monitoring systems, sensor-based vehicle flow management, and adaptive traffic management will be important steps to improve the overall performance of the national road network.

Fifth, the sustainable financing aspect needs to be a major concern. Dependence on the APBN must be reduced through the development of a PPP model and green financing schemes. Green financing allows infrastructure projects to obtain funds from environmentally oriented investors with social returns. To attract investors, fiscal incentive policies and project sustainability guarantees are needed, including environmental certification and a credible sustainability audit system. With this financing model, road construction is not only the responsibility of the state, but also the result of collaboration between the government, industry, and the community. Sixth, strengthening governance and public participation is a determining factor for the success of sustainable development. Local communities, especially indigenous communities in Kalimantan such as Dayak, Kutai, and Paser, must be actively involved in all stages of the project, from planning, implementation, to evaluation. Public participation is not just an administrative formality, but a forum to ensure that infrastructure projects are aligned with local social needs and cultural values. This approach will also increase the social legitimacy of the project and prevent land conflicts that often arise in large-scale development. Seventh, the government needs to develop a cross-sectoral policy framework that ensures synergy between infrastructure development, environmental policies, and regional economic strategies. Road construction should be part of a broader national strategy—namely strengthening domestic connectivity and economic integration in the ASEAN region. In the geopolitical context, the road network in Kalimantan has the potential to become a strategic corridor of the Trans-Borneo Highway connecting Indonesia, Malaysia, and Brunei. However, in order for this potential to be optimally realized, it is necessary to harmonize cross-border logistics policies, simplify customs procedures, and strengthen regional cooperation in the fields of transportation and the environment. Eighth, efforts to reduce emissions and adapt to climate change must be integrated in every stage of development. Kalimantan as one of the lungs of the world has a global responsibility in maintaining carbon balance. Therefore, every road project must be equipped with an EMP that includes greenhouse gas mitigation strategies, rehabilitation of former construction land, and reforestation along road corridors. The use of renewable energy sources in construction and maintenance activities must also become a new operational standard to reduce the carbon footprint of the transportation sector. Ninth, institutional capacity and improvement of human resource competence in the fields of civil engineering, environment, and public policy are needed. Regional training centers and university-industry collaboration can accelerate technology transfer and enhance local capabilities in managing sustainable projects. The government also needs to strengthen the monitoring and evaluation system through independent institutions so that the development process runs transparently, efficiently, and in accordance with global sustainability standards. This recommendation confirms that sustainable infrastructure development cannot be achieved through technical approaches alone. Synergy between technology, policies, governance, and social values is needed that ensures justice between regions. By integrating the principles of green infrastructure, technological innovation, and meaningful public participation, the construction of national roads in Kalimantan can become a model for sustainable infrastructure development in the world's tropics—a transportation system that not only connects regions, but also bridges the well-being, knowledge, and preservation of nature for future generations.

14.3. Suggestions for Advanced Research

In the face of increasingly complex infrastructure development dynamics, advanced research is the main pillar to ensure that the development process is not only oriented to physical output, but also to long-term outcomes in the form of social, economic, and ecological sustainability. The experience of the construction of the national road network in Kalimantan shows that many technical and non-technical aspects still require scientific deepening and a multidisciplinary approach. Therefore, further research needs to be directed towards developing innovation, strengthening evidence-based policies, and building resilient national scientific and institutional capacity.

1. Direction of Technical Research and Infrastructure Engineering

The first area that needs priority is technical research and infrastructure engineering adaptive to the geotechnical conditions and tropical climate of Kalimantan. The biggest challenges in the region stem from the characteristics of peatlands and alluvial soils that have low carrying capacity, as well as high rainfall intensity throughout the year. Future research should focus on developing more efficient and environmentally friendly soil stabilization technologies. For example, the use of industrial waste-based additives such as fly ash, steel slag, and natural fibers from local plants needs to be comprehensively tested to determine their long-term performance against deformation, water absorption, and compressive strength. In addition, research on long-life pavement structures is crucial to reduce the life-cycle cost of road infrastructure. The composite pavement model and the use of RAP can be an alternative in the context of resource efficiency. Experimental studies and numerical modelling of the performance of pavements under heavy traffic loads, particularly mining and logistics vehicles, are also needed to make the technical design more accurate and contextual to the field conditions in Kalimantan. Research also needs to be directed at the development of SuDS technology that is able to manage rainwater runoff effectively without causing erosion and local flooding. A combination of civil engineering and ecological approaches such as vegetative systems (bio-swales) and natural retention ponds can be an innovative solution for areas with extreme rainfall. On the other hand, the topic of sensor-based road condition monitoring and AI needs to be expanded to support predictive maintenance systems. The use of the IoT to collect real-time data on soil deformation, cracks, and moisture can improve the accuracy of analysis and accelerate technical decision-making by road management agencies.

2. Socio-Economic and Spatial Research Directions

The second aspect that is very important to study further is the long-term social and economic impact of national road development on local communities and regional development patterns. Although connectivity is increasing, not all regions have enjoyed economic benefits equally. Therefore, socio-economic research needs to trace the relationship between road construction and income distribution, changes in work structures, population mobility, and land use transformation. Especially in Kalimantan, research needs to evaluate the extent to which road construction has contributed to the strengthening of the economy of the interior and customary areas. Spatial econometrics and GWR based studies can be used to identify patterns of spatial inequality and measure the multiplier effect of road construction on local economic growth. In addition, research topics on accessibility to basic services (education, health, clean water, and markets) are important to assess the success of development from the perspective of community welfare. In the socio-cultural context, road construction also brings changes to the identity of the community and the way of life of indigenous peoples. Increased mobility can accelerate the flow of urbanization and change patterns of social interaction. Anthropological and sociological research is needed to understand how local communities adapt to these changes, as well as how traditional values can be integrated into sustainable development models. A participatory approach in this kind of research will provide a more inclusive perspective on infrastructure development. In addition, further research needs to examine the macroeconomic efficiency of national road projects using the CBA and LCA approaches. These studies will help measure the economic added value generated compared to the social and environmental costs that arise. Thus, policymakers can formulate development priorities based on economic effectiveness and regional justice.

3. Direction of Environmental and Sustainability Research

The third area that is no less important is research on the ecological impact and application of green technology in road infrastructure. Kalimantan, as a center of tropical biodiversity, faces a high risk of habitat loss due to land fragmentation and deforestation triggered by road construction. Further research needs to map in detail the ecological impact of road projects on flora and fauna diversity using remote sensing and ecological modeling approaches. In addition, it is necessary to develop a study on the effectiveness of the implementation of the concept of wildlife corridors that allow the movement of wildlife without being interrupted by the existence of roads. These kinds of studies can measure the effectiveness of animal bridges, green tunnels, and migration routes designed as part of eco-road engineering. This approach is not only relevant for Borneo, but can also serve as a model for other tropical regions in Southeast Asia. Further research also needs to evaluate carbon emissions from the road construction sector and its potential reduction through material technology innovation and the use of renewable energy. Carbon footprint analysis of various stages of the project—from the production of building materials to the operation of vehicles on the road—will provide a scientific basis for the decarbonization policy of the transportation sector. In this context, research cooperation between universities, industry, and government agencies need to be strengthened through the establishment of a consortium for green infrastructure research at the national level. In addition, the issue of adaptation to climate change must be the main focus of future research. National road projects in Borneo must be designed to be resistant to floods, landslides, and changes in extreme weather patterns. Studies on climate-resilient infrastructure design can help formulate new technical standards that take into account long-term climate variability. The integration of climate and hydrological data in road planning will strengthen the resilience of transportation systems to the risk of natural disasters.

4. Policy and Institutional Research Direction

In addition to technical and environmental aspects, it is necessary to develop public and institutional policy research that focuses on sustainable infrastructure governance. Studies on the effectiveness of cross-sectoral policies, green financing mechanisms, and the PPP model need to be expanded. Empirical research can help assess the success of PSO policies in supporting equitable distribution of transportation development. Research also needs to examine the mechanisms of public participation and social oversight in major infrastructure projects. Studies of participatory practices at the local level can identify effective governance models to prevent land conflicts and increase transparency in budget use. By involving local communities in the decision-making process, the construction of national roads will be more inclusive and in accordance with the real needs of the community. In addition, policy research needs to evaluate the synchronization of regulations between the central and local governments related to licensing, land acquisition, and development technical standards. Regulatory disharmony is often a source of bureaucratic bottlenecks and project delays. Comparative policy studies between regions can provide recommendations for legal and institutional reforms so that national infrastructure systems are more adaptive to global socio-economic and environmental changes.

5. Integration of Interdisciplinary Research and National Collaboration

In closing, further research in the field of national road construction must be carried out in an interdisciplinary and collaborative manner. Development challenges cannot be solved by just one field of knowledge. Collaboration between civil engineering, environmental engineering, regional economics, policy science, and socio-cultural sciences is needed to produce comprehensive solutions. The central government can play a role as a facilitator in building national research networks involving universities, research institutions, and the industrial sector. Especially for Kalimantan, the establishment of a tropical infrastructure and environment research center will be a strategic step to produce innovations based on local contexts. This research center can focus on the development of adaptive material technology, sustainable transportation systems, and participatory policy models. In addition to strengthening national capacity, this collaboration also has the potential to make Indonesia an international reference in sustainable infrastructure development in tropical regions. A comprehensive follow-up research direction—covering technical, socio-economic, environmental, and policy dimensions—will ensure that national road construction in Kalimantan is not just a physical project, but a large laboratory for innovation and sustainability. Integrated and future-oriented research will be the scientific foundation for the achievement of a resilient, climate change-adaptive, and socially just national infrastructure system for all Indonesians.

14.4. Government, Industry, and Community Stakeholders

The construction of a national road network in Kalimantan, as discussed in the previous chapters, cannot be seen as a mere technical project, but rather as a collective effort to build the foundations of a new just and sustainable civilization. Within this framework, the success of development depends heavily on the active role and synergy between three main stakeholder groups: government, industry, and society. Each party has a unique responsibility and contribution in ensuring that infrastructure development not only creates physical connectivity, but also strengthens social, environmental, and economic resilience.

1. Government: Transformation Leader and Guardian of Governance

The government, both at the central and regional levels, has a strategic role as a guide and guarantor of the direction of inclusive development. As a policymaker, the government must ensure that every stage of national road development in Kalimantan is based on the principles of good governance, sustainability, and public participation. First, the government needs to strengthen data-based planning and evidence-based policies. In the context of road construction, decision-making must be supported by technical data such as the PCI, traffic volume, spatial analysis, and socio-economic data of the affected communities. The use of big data and AI in infrastructure planning can help governments determine investment priorities, predict long-term impacts, and optimize budget allocation. Second, the government must be a pioneer in the application of green development principles through binding and measurable policies. Every road project must be required to undergo a comprehensive EIA, covering carbon, biodiversity, and socio-cultural aspects. The central government can issue national guidelines on green road standards that regulate the use of recycled materials, energy efficiency, and sustainable drainage systems. Thus, road construction policies are no longer only oriented to physical output, but also to ecological impacts and long-term sustainability. Third, the government needs to strengthen cross-sector and cross-regional coordination. The development of the national road network in Kalimantan cannot run optimally without synergy between ministries, institutions, and local governments. Poor coordination often leads to project overlap, delays, and budget waste. Therefore, it is necessary to establish an integrated coordination system such as the RICC which functions to integrate policies between the Ministry of Public Works and Housing, the Ministry of Transportation, the Ministry of Environment and Forestry, and Bappenas.

Fourth, in the social context, the government must ensure the protection of the rights of local communities and indigenous communities. Land acquisition must be carried out fairly, transparently, and respectfully the rights of customs. The public consultation mechanism must be carried out from the planning stage so that the public has space to express their aspirations and concerns. In addition, the government needs to ensure that the economic benefits of infrastructure projects can be felt directly by the community through local empowerment programs, workforce training, and support for MSMEs along the road corridor. Finally, the government must be an example in transparency and accountability. Oversight of projects should be conducted openly through an online public information system that displays physical, financial, and social impact progress. Collaboration with independent audit bodies and civil society will strengthen public confidence in the national development program.

2. Industry: Motor Innovation and Strategic Partner

The industrial sector has a great responsibility as the main driver of the implementation of technology and innovation in infrastructure development. In the era of sustainable development, the role of industry is not only limited to construction implementers, but also as an agent of technological transformation and the green economy. First, construction and material manufacturing companies must play an active role in the development of environmentally friendly and energy-efficient technologies. The use of recycled asphalt (reclaimed asphalt pavement), concrete with environmentally friendly additives, and warm mix asphalt technology can significantly reduce carbon emissions. Industries also need to invest in R&D to create new innovations in soil stabilization, composite materials, and pavement systems that are adaptive to climate change. Second, the industry is expected to implement the concept of CSR which is in line with sustainable development goals. CSR programs should not only be philanthropic, but are geared towards strengthening the capacity of local communities around projects. For example, training of local workers in civil engineering, environmental management, and entrepreneurship can increase the direct economic impact of infrastructure development. Industry can also play a role as a facilitator in building economic partnerships between communities and projects through the community-based enterprise model. Third, companies need to adopt an EMS according to the ISO 14001 standard as part of the organizational culture. With this system, every stage of the project, from planning, implementation, to post-construction, can be closely monitored to remain in accordance with sustainability principles. Reporting of emissions, energy use, and construction waste should be done regularly and audited by an independent agency. Fourth, the industry is expected to support the digitalization of the construction process through the application of BIM, digital twins, and the IoT for real-time project monitoring. Digitalization not only improves time and cost efficiency, but also strengthens transparency and risk mitigation. In addition, innovations in data-driven project management will help governments and contractors achieve national efficiency targets in infrastructure development. Fifth, the industrial sector must strengthen partnerships with research institutions and universities to accelerate knowledge and technology transfer. This collaboration will strengthen the national innovation ecosystem in the fields of road engineering, materials, and intelligent transportation systems. With the active involvement of the industry, research results do not only stop at the academic level, but can be implemented in real terms in the field.

3. Community: Supervisors, Partners, and Beneficiaries

The community is the most affected party as well as the direct beneficiary of the construction of the national road network. Therefore, the position of the community should not be just as an object of development, but as an active subject that plays a role in supervision, utilization, and preservation of infrastructure. First, the community needs to be given access to information and a wide space for participation in each stage of development. The government and contractors are obliged to open a public consultation mechanism and feedback loop so that the public can be involved in social supervision of the project. This involvement not only increases transparency, but also strengthens a sense of ownership of development outcomes. Second, the community can play a role as social auditors in ensuring that projects run according to ethical and environmental standards. The involvement of civil society organizations, environmental NGOs, and indigenous institutions will help prevent corrupt practices, human rights violations, and ecological damage. Community participation is also important to maintain project security and minimize potential land conflicts. Third, in the context of the local economy, road construction opens up new opportunities for community-based economic development. Increased accessibility allows communities to develop transportation businesses, trade in agricultural products, and local tourism. Therefore, the community needs to be encouraged to utilize infrastructure productively through entrepreneurship training, access to micro capital, and strengthening local cooperatives. Fourth, the community has an important role in the long-term maintenance of infrastructure through community-based maintenance programs. This program has proven effective in various developing countries in maintaining the sustainability of road functions, especially in rural areas. The government can engage the community through labor-intensive mechanisms for routine road maintenance, drainage, and green open space along road corridors. Fifth, the community must also be part of the environmental awareness and transportation safety cultural movement. Education and public campaigns on the importance of maintaining road cleanliness, obeying traffic signs, and preserving vegetation along the road will strengthen the social value of development. Good infrastructure will only be beneficial if the community has a collective awareness to maintain it.

14.5. Synergistic Collaboration Towards a Sustainable Future

Relationships between government, industry, and society must be built on the basis of equal partnership and mutual trust. The government plays a role as a regulator and facilitator, the industry as a motor of innovation and technical implementer, while the community as a supervisor as well as a beneficiary. This synergy will create a triple helix collaboration which is the main prerequisite for the success of sustainable development. To realize this, a permanent coordination forum such as the FIKB is needed which brings together all stakeholders in one joint communication and evaluation system. These forums can serve as social and policy laboratories, where ideas, data, and cross-sector solutions meet. Through this mechanism, every strategic decision can be made in an inclusive, transparent, and science-based manner. Overall, the key message for all stakeholders is that the construction of the national road network in Kalimantan should not only be measured by the length of asphalt stretched, but by how much it is able to connect people, nature, and human values. The road must be a symbol of progress that is in favor of the people and the environment. With strong cross-sector collaboration, a commitment to sustainability, and a collective moral awareness, infrastructure development in Kalimantan can be a milestone for Indonesia in building a resilient, green, and equitable future. The construction of the National Road Network in Kalimantan is a reflection of the nation's determination to realize connectivity and equitable development throughout Indonesia. Through the analysis presented in Chapter 14—including general conclusions, strategic recommendations, follow-up research suggestions, and messages to stakeholders—it can be concluded that the success of infrastructure development is not only measured by physical achievements, but also by the extent to which the infrastructure is able to strengthen national competitiveness, improve community welfare, and maintain environmental sustainability. The future of road construction in Kalimantan demands a new paradigm: development based on science, technology, and collaboration. The government is expected to continue to strengthen evidence-based governance and policies; industry is required to be a driver of environmentally friendly technological innovation; Meanwhile, the community needs to take an active role as supervisors as well as guardians of development results. Only through the synergy of these three elements, the development of the national road network can be the driving force for creating a balance between economic progress and ecological sustainability. Finally, this chapter emphasizes that road construction in Kalimantan is not just an infrastructure project, but also a reflection of the nation's vision towards a resilient, green, and inclusive Indonesia. With the spirit of collaboration and commitment to sustainable development, the roads built today are expected to be a link for progress, unity, and a better future for all Indonesian people.

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