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Message from the Chief Editor

Welcome to the 2026 issue of the Journal of the Road Engineering Association of Asia and Australasia (JREAAA).

Building on the successful launch of our inaugural issue in 2025, this second issue reflects REAAA's continued commitment to providing a platform for sharing research, practical knowledge, and emerging perspectives in road engineering across Asia and Australasia.

JREAAA remains dedicated to advancing safer, more efficient, resilient, and sustainable transport infrastructure by fostering regional collaboration and promoting innovation and best practices among researchers, practitioners, policymakers, and industry professionals.

This year, we are pleased to present five papers that demonstrate the expertise and diverse contributions of the road engineering community. We extend our sincere appreciation to all authors, reviewers, and members of the editorial team whose dedication and valuable contributions have made this issue possible.

We hope the knowledge shared in this issue will encourage further discussion, collaboration, and innovation throughout the region. Your continued support and feedback are essential to the growth and success of JREAAA.
On behalf of the editorial team, thank you, and we hope you find this issue informative and valuable.

Sincerely,
Chief Editor, JREAAA

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The journal's primary objective is to promote and advance the science and practice of road engineering and its related professions. By publishing high-quality research articles, case studies, and technical reviews, JREAAA supports continuous learning, professional development, and the elevation of road engineering standards. The journal is also dedicated to encouraging the sharing of innovative ideas and best practices, ultimately contributing to the development of safer, more efficient, and sustainable road infrastructure throughout the region.

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Incentive Based Programme to Improve Gender and Equality in Regional Roads in Indonesia

Dedy Gunawan[1], Alfa Ash-Shiddiqi[1,*],
*Corresponding author: adibalfa@gmail.com, adibalfa@pu.go.id

[1]*Directorate General of Highways, Ministry of Public Works, South Jakarta, Jakarta, Indonesia*

ABSTRACT

Regional roads in Indonesia are critical for mobility, economic growth, and social inclusion, yet they face persistent challenges of inadequate governance, limited maintenance budgets, and inequitable access for vulnerable groups. Building on the experience of incentive-based programs such as PRIM and RRGP, this paper explores how similar mechanisms can be extended to advance gender equality and social inclusion (GESI) in regional road provision. By linking financial incentives and performance-based grants to measurable outcomes in gender participation, inclusivity, and community empowerment, local governments can be encouraged to adopt more equitable planning, design, and implementation practices. Case study evidence from Nusa Tenggara Barat and Lombok Barat demonstrates that incentive schemes have successfully introduced governance reforms, improved service delivery, and expanded opportunities for women and marginalized groups to participate in road management forums, consultations, and road-related economic activities. This study proposes a framework for scaling up gender-responsive incentive programs across Indonesia, integrating GESI indicators into governance verification, and aligning with national commitments to sustainable infrastructure and the Sustainable Development Goals (SDGs). The findings highlight that incentive-based schemes not only improve technical road stability but also catalyze institutional change toward greater inclusivity, transparency, and equity in regional road governance.

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1. Introduction

In Indonesia, regional roads play a fundamental role in ensuring connectivity, supporting economic activities, and promoting social inclusion. Comprising nearly 90 percent of the total national road network, these provincial, district, and city roads serve as the backbone of daily mobility for millions of Indonesians (Directorate General of Highways, 2021). However, persistent challenges in financing, governance, and institutional capacity have resulted in a significant service gap between regional and national roads. Many local governments struggle with budgetary constraints, reliance on short-term project cycles, and limited institutional resources, leading to inadequate routine maintenance, deteriorating infrastructure quality, and unequal access to safe and reliable mobility (Gunawan, et al, 2021).

Recognizing these gaps, the Government of Indonesia, with support from development partners, introduced incentive-based grant programs such as the Provincial Road Improvements and Maintenance (PRIM) and the Regional Road Grant Program (RRGP). These schemes link financial transfers from the central government to local governments with performance indicators related to governance reforms, technical delivery, and improved accountability (DFAT, 2023). Evaluations have shown that such programs foster better planning, prioritization of preservation over new construction, adoption of long-segment contracts, and increased transparency through mechanisms such as the Road Transport and Traffic Forum (RTTF) (DFAT, 2015). Beyond technical improvements, these programs have also encouraged local governments to engage in cross-cutting issues such as anti-corruption, disability access, and gender participation.

The gender dimension, however, remains underexplored and often underutilized in the broader governance of regional roads. While evidence from PRIM and RRGP indicates that women participated in consultation processes and benefited from safer road shoulders, improved sidewalks, and better access to schools and markets, their involvement was limited in scope and scale (UNDP Indonesia, 2021). Women accounted for 7–20 percent of participants in consultations and project-related activities, yet their influence in decision-making, budgeting, and institutional leadership remained minimal. Similarly, opportunities for women-owned enterprises and marginalized groups to engage in road sector value chains—such as routine maintenance services, supply of local materials, or roadside economic activities—are rarely formalized in program design. This signals a missed opportunity to integrate Gender Equality and Social Inclusion (GESI) principles systematically into road governance.

In Indonesia, gender inequality in transport is manifested not only in limited female representation in the construction and management workforce but also in unequal access to safe and affordable mobility.

Women, children, the elderly, and people with disabilities often experience disproportionate risks on poorly maintained regional roads, including exposure to accidents, limited pedestrian facilities, and inadequate lighting. These inequities reduce their participation in education, healthcare, and economic opportunities, perpetuating cycles of disadvantage. The National Road Safety Plan (RUNK 2021–2040) and Indonesia's commitment to the Sustainable Development Goals (SDGs), particularly SDG 5 (Gender Equality) and SDG 9 (Industry, Innovation, and Infrastructure), emphasize the need to address these disparities within infrastructure policy and practice. (United Nations, 2015).

This paper builds on the experiences of PRIM and RRGP to propose an Incentive-Based Programme to Improve Gender and Equality in Regional Roads in Indonesia. Specifically, it seeks to answer following questions: (i) how can existing governance-focused incentive schemes be adapted to strengthen gender equality and inclusivity in the road sector? (ii) what lessons can be drawn from case studies where women's participation and benefits were evident, albeit limited? and (iii) what framework can guide the systematic integration of GESI indicators into future incentive-based grant mechanisms? By addressing these questions, the paper contributes to a growing discourse on how infrastructure policy can transcend traditional engineering goals and embrace a more holistic approach that recognizes roads as enablers of equitable development. It argues that incentive-based programs, if designed with gender and equality dimensions in mind, can become powerful instruments to transform not only road governance but also the broader socio-economic outcomes of Indonesia's regional road sector.

2. Method

This study employs a qualitative case study approach supported by document analysis and comparative review. The methodology is structured around three steps: a review of existing incentive-based programs in Indonesia's road sector, integration of gender equality and social inclusion (GESI) perspectives into the analysis, and synthesis of lessons learned to propose a framework for future implementation.

The first stage examines the design and outcomes of incentive-based programs such as the Provincial Road Improvement and Maintenance (PRIM) and the Regional Road Grant Program (RRGP). These programs provide the foundation for understanding how fiscal incentives have been linked to governance reforms in regional road maintenance (Gunawan et al, 2021). Policy manuals, evaluation reports, and technical guidelines issued by the Ministry of Public Works and Housing, the Ministry of Finance, and development partners are analyzed to identify governance items, performance verification mechanisms, and reimbursement processes (DFAT, 2023).

To ground the analysis, two case studies were selected: Nusa Tenggara Barat (NTB) Province and Lombok Barat District, both of which participated in PRIM between 2013 and 2019. These sites were chosen due to their pioneering role in implementing incentive-based programs and their documented efforts to integrate gender-related activities. Secondary data include program evaluations, project management manuals, and peer reviews. Comparative analysis is conducted between PRIM-implementing areas and non-implementing regions to highlight differences in road stability, governance practices, and community participation (DFAT, 2015).

The study then applies a GESI lens to assess the extent of women's participation, inclusivity of consultation forums, and gender-sensitive design measures such as pedestrian sidewalks, school-zone safety, and drainage. Key indicators include: (i) percentage of women participating in Road Transport and Traffic Forum (RTTF) meetings, (ii) representation of women in contractor and consultant roles, and (iii) opportunities for women-owned enterprises in maintenance-related value chains. These indicators were derived from project reports, program guidelines, and United Nations Development Programme (UNDP) recommendations for inclusive infrastructure (UNDP Indonesia, 2021).

Finally, the study synthesizes findings to propose a conceptual framework for integrating gender equality into future incentive-based road programs. This involves aligning existing governance verification items—such as transparency, accountability, and efficiency—with gender-specific performance indicators. Comparative insights are drawn from both Indonesian experiences and international best practices on gender mainstreaming in infrastructure, particularly those promoted under the Sustainable Development Goals (United Nations, 2015).

3. Governance and Gender in Regional Roads

The governance of Regional Road in Indonesia has historically centered on technical performance and institutional capacity, with limited attention to gender equality and social inclusion (GESI). The introduction of incentive-based programs such as the Provincial Road Improvement and Maintenance (PRIM) and the Regional Road Grant Program (RRGP) has gradually shifted the focus toward more participatory and accountable practices. However, while these programs represent an important step in enhancing governance, their integration of gender dimensions remains partial and uneven.

3.1. Governance Challenges in Regional Roads

Governance of regional roads is complex due to overlapping responsibilities between central and local governments, inadequate planning, and weak accountability mechanisms. As noted by Gunawan et al (2021), regional governments often prioritize new road construction over routine maintenance, while budgeting and programming are influenced by political considerations rather than technical assessments. The lack of reliable road asset data and weak institutional capacity have further undermined planning and sustainability. Incentive-based programs were designed to address these weaknesses by tying fiscal transfers to governance reforms, including improved transparency, community engagement, and stronger verification processes (Davies et al, 2005).

3.2. Gender Gaps

Despite improvements in governance mechanisms, gender representation within decision-making processes remains limited. Evaluations of PRIM highlighted that women's participation in governance structures such as the Road Transport and Traffic Forum (RTTF) was present but inconsistent (DFAT, 2015). In some pilot locations, women accounted for 10–20 percent of consultation participants, while in others participation was negligible. Even where women were present, they often played consultative rather than decision-making roles.

The inclusion of gender in PRIM governance indicators was largely focused on representation targets, rather than substantive influence. Contractors and consultants were encouraged to hire women, yet these positions were frequently limited to low-skilled tasks. Similarly, women's voices in consultations were often not translated into binding decisions on road programming or design (DFAT, 2015). This illustrates a broader pattern where gender inclusion was treated as an "add-on" rather than a mainstreamed governance principle.

3.3. Benefits and Limitations of Gender Integration in PRIM

Nonetheless, PRIM did provide openings for women and marginalized groups to benefit from improved road governance. In Nusa Tenggara Barat (NTB), program guidelines required public consultations with women and vulnerable populations. As a result, women's participation in road safety discussions—such as the provision of sidewalks, shoulders, and school-zone facilities—increased (Gunawan et al., 2021). Evaluations documented that women and girl gained improved access to markets, schools, and health services, while roadside economic activities—such as food stalls and small businesses—expanded women's income opportunities (DFAT, 2021).

However, the scope of gender benefits remained limited to secondary effects rather than structural reforms. For example, while road safety facilities such as sidewalks improved conditions for women and children, few mechanisms ensured that women could influence budget allocations or procurement decisions. Similarly, while women-owned businesses benefitted from increased traffic, they were not systematically included in contractor supply chains or routine maintenance contracts (DFAT, 2015).

3.4. International and National Gender Policy

The limited integration of gender into regional road governance contrasts with broader national and international commitments. Indonesia's Gender Mainstreaming Policy (Inpres No. 9/2000) and the National Road Safety Plan (RUNK 2021–2040) both underscore the need for gender-sensitive planning (Bappenas, 2020). At the international level, the Sustainable Development Goals (SDGs) call for gender equality (SDG 5) and inclusive infrastructure (SDG 9). The United Nations Development Programme (UNDP) has further emphasized that gender equality in infrastructure is not only a social justice imperative but also improves governance outcomes by strengthening accountability, transparency, and service delivery (UNDP Indonesia, 2021).

Yet, evaluations of PRIM demonstrate that translating these commitments into practice requires clear performance indicators, capacity building, and institutional incentives (DFAT, 2021). Without embedding gender into the core governance framework—through measurable targets, monitoring, and enforcement—gender participation risks remaining symbolic.

4. Case Study Analysis

4.1. Background: Why NTB and Lombok Barat?

Nusa Tenggara Barat (NTB) Province and Lombok Barat District represent pioneering sites for the implementation of incentive-based programs in Indonesia's regional road sector. As the first province to pilot the Provincial Road Improvement and Maintenance (PRIM) program in 2013, NTB became a testing ground for the adaptation of fiscal incentives to promote governance reforms in road provision (Gunawan et al, 2021). The program was initially intended for three years, but was extended to six years due to both the challenges and the potential demonstrated during early implementation. Lombok Barat District was selected as a secondary pilot site in 2017, building on NTB's experiences. By then, the central government sought to replicate lessons learned in NTB and apply them at the district level, where fiscal and human resource constraints are typically greater. Lombok Barat's location within the Mandalika National Tourism Strategic Area made it particularly important as improved roads were expected to unlock tourism and local economic opportunities (DFAT, 2021). The two cases are thus complementary: NTB illustrates how governance reforms can be introduced at the provincial level, while Lombok Barat highlights how these reforms can be adapted at the district level. Together, they provide valuable lessons for scaling up incentive-based programs across Indonesia.

4.2. Road Governance Before PRIM

Prior to PRIM, both NTB Province and Lombok Barat District faced common governance and financing challenges. Road maintenance was chronically underfunded, with local governments allocating only 10–15 percent of their road budgets for routine maintenance, compared to the recommended 30–45 million rupiah per kilometer (Gunawan et al., 2021). Visual road surveys were conducted infrequently and lacked technical rigor, leading to unreliable data for programming.

Governance weaknesses were equally acute. Programming and budgeting were heavily influenced by political interests rather than technical priorities. Many contracts were awarded using small-package schemes worth around Rp 250 million, allowing contractors to be selected from a limited pool without full competitive bidding (Gunawan et al., 2021). The result was poor construction quality, rapid deterioration, and a cycle of reconstruction–damage–rehabilitation that was both costly and unsustainable.

From a gender perspective, the governance system was almost entirely gender-blind. Women's voices were absent from road planning, and there were no institutional mechanisms requiring the inclusion of women or marginalized groups in consultation or decision-making. As noted in DFAT's gender strategy, women and vulnerable populations—who disproportionately rely on safe pedestrian infrastructure—were rarely considered in programming decisions (DFAT, 2015).

4.3. Implementation of PRIM in NTB

The PRIM program introduced a new governance and financing model based on pre-financing by local governments and reimbursement by the central government upon verification of outputs. This model incentivized NTB to prioritize maintenance, introduce governance reforms, and demonstrate accountability in order to access central funds (Gunawan et al., 2021).

Key reforms included:

1. Use of the Provincial Road Management System (PRMS): NTB was required to base programming and budgeting on accurate road asset data collected through technical surveys, including International Roughness Index (IRI) measurements.
2. Long-segment contracts: Replacing small-package contracts, PRIM introduced corridor-based contracts covering 50–135 kilometers, improving efficiency and quality.
3. Activation of the Road Transport and Traffic Forum (RTTF): A participatory platform that included representatives from government, civil society, and NGOs, including women's groups.
4. Public consultations and transparency: Project packages and budgets were published online and discussed in public meetings.
5. Governance indicators: NTB had to meet progressively stricter governance criteria—expanding from 4 items in 2013 to over 60 by 2020—in order to receive full incentive reimbursements (DFAT, 2021).

From a gender perspective, PRIM required women's participation in RTTF meetings and public consultations. Women's NGOs were invited to provide input, and program guidelines encouraged contractors to employ women and consider safety facilities such as sidewalks, school zones, and drainage improvements (DFAT, 2015).

The outcomes in NTB were significant, both in terms of technical performance and social inclusion, as follows:

1. Road performance improvement: Good road conditions improved from 52.9% in 2010 to 83.65% in 2019 (Gunawan et al., 2021). This exceeded the national target of 75% for provincial roads.
2. Governance reforms: NTB institutionalized the use of PRMS for planning, improved procurement transparency, and established a Road Maintenance Management Team (RMMT) to sustain reforms beyond PRIM.
3. Gender participation: Women accounted for 10–15% of RTTF participants and 14–20% of participants in public consultations (DFAT, 2015). Women's NGOs successfully advocated for safety facilities such as sidewalks and school-zone signage.
4. Economic opportunities: Women benefitted indirectly through roadside businesses, selling food, fuel, and services to road workers and increased traffic (DFAT, 2021). Improved mobility expanded women's access to markets, schools, and health facilities.

Yet, the program's gender impact was uneven. While participation quotas were met, women's influence on final programming decisions remained limited. Employment of women in contractor and consultant roles was small, often confined to administrative or support positions. DFAT's evaluation noted that while PRIM created spaces for women, these spaces were not always used to advance transformative gender equality (DFAT, 2015).

4.4. PRIM Implementation in Lombok Barat District

In 2017, PRIM was introduced in Lombok Barat District, which managed around 572 kilometers of road, of which only 60% was in stable condition at the start. The district faced even greater resource constraints than NTB Province, but benefitted from lessons learned in the provincial pilot.

Lombok Barat adopted the corridor management contract model, grouping several road links into larger packages. Between 2017 and 2018, three contracts were signed covering 66–145 kilometers each, with values ranging from Rp 12–16 billion. This approach increased efficiency by reducing the administrative burden of multiple small contracts and improving contractor performance.

Governance reforms were also extended: RTTF was activated with stronger participation from civil society (see Figure 3), and the district government joined the Construction Sector Transparency (CoST) initiative, which promotes accountability through public disclosure of project data (Gunawan et al., 2021).

Gender integration followed similar patterns to NTB. Women participated in RTTF consultations and benefitted from safety facilities. For example, School Safety Zone sidewalks and drainage improvements were explicitly designed to support pedestrian safety, especially for school children (see Figure 2) and women carrying goods to markets. Contractors also reported modest employment of women, mainly in routine maintenance and support roles (DFAT, 2015).

Figure 1: Participation of women engineer in the PRIM project.

Figure 2: School Safety Zone implemented for gender and inclusion.


Figure 3: Group discussion involving women on the project preparation.

Despite these advances, challenges remained. Women's representation in formal road management teams was limited, and gender-sensitive procurement requirements were weakly enforced. As in NTB, gender inclusion was more effective at the consultation and community benefit level than in institutional decision-making. Resume of the PRIM implementation is shown on Table 1.

Table 1: PRIM Implementation in NTB and Lombok Barat

Dimension	Nusa Tenggara Barat (NTB) Province	Lombok Barat District	Comparative Insights
Initial Conditions	Road stability 52.9% (2010); underfunded maintenance; weak data and governance (Gunawan et al., 2021)	Road stability 55.3% (2015); limited fiscal capacity; similar governance weaknesses (DFAT, 2021)	Both faced systemic underfunding and political-driven budgeting
Governance Reforms	Introduced PRMS for data-driven planning; long-segment contracts (50–135 km); RTTF activated	Adopted corridor management contracts (66–145 km); RTTF activated; joined CoST for transparency	Similar governance reforms; Lombok Barat added transparency via CoST
Gender Participation	10–15% of RTTF participants; women's NGOs engaged; limited influence in budgeting (DFAT, 2015)	10–15% participation in RTTF; women more vocal due to prior exposure; similar representation	Participation rates similar; Lombok Barat showed stronger engagement quality
Employment & Economic Opportunities	Women employed (7–13% contractor staff; 7–9% consultant staff); roadside businesses expanded post-upgrade (DFAT, 2015)	Women in routine maintenance and informal roles; roadside businesses tied to tourism growth	Employment remained limited; both showed indirect economic benefits through businesses
Safety & Access Outcomes	Improved sidewalks, drainage, school-zone signage; safer mobility for women/children (Gunawan et al., 2021)	Similar safety improvements; focus on tourism corridor safety and pedestrian facilities	Both delivered gender-sensitive infrastructure, improving access
Road Stability Outcomes	Increased from 52.9% (2010) to 83.65% (2019)	Increased from 55.3% (2015) to 62.8% (2019)	NTB's improvement faster; Lombok Barat slower but positive
Institutionalization	Established Road Maintenance Management Team (RMMT) for sustainability	Joined CoST, embedding infrastructure transparency	Both institutionalized reforms differently—NTB via technical capacity, Lombok Barat via transparency
Challenges	Women's participation often symbolic; low representation in decision-making; limited procurement inclusion	Similar limitations; women's roles still marginal in contracting and road agencies	Structural gender gaps persist in both cases
Key Lessons	Incentives drive governance reform but need stronger GESI mainstreaming	Transparency and local participation can improve engagement quality	Incentive schemes effective, but gender requires systematic integration

4.5. Insights and Lesson Learned

Several key lessons emerge from these case studies:

1. Incentives can drive governance reform. Linking fiscal transfers to governance performance created strong motivation for both NTB and Lombok Barat to adopt reforms.
2. Gender requires more than quotas. While women's participation increased, influence on decision-making remained limited. Future programs must embed gender indicators into governance verification.
3. Economic benefits are real but indirect. Women benefitted from roadside businesses and improved access, but rarely from formal contracting opportunities.
4. Institutionalization is critical. NTB's RMMTs and Lombok Barat's CoST membership suggest pathways for sustaining reforms, but gender mainstreaming remains weak without explicit institutional mandates.
5. Capacity building is essential. Both cases highlight the need for training in gender audits, inclusive design, and participatory governance to enable more meaningful integration of GESI principles.

The PRIM/RRGP scheme introduced governance reforms (data-driven planning, corridor contracts, and transparency) alongside gender inclusion measures (women in RTTF, gender-sensitive design, and women's employment). These measures produced both technical outcomes (improved stability and sustainable maintenance) and social outcomes (safer mobility, expanded women's economic opportunities, and greater access for vulnerable groups). The outcomes reinforced governance structures, creating a feedback loop where gender equality and inclusivity became progressively mainstreamed into road management practices (see Figure 4).

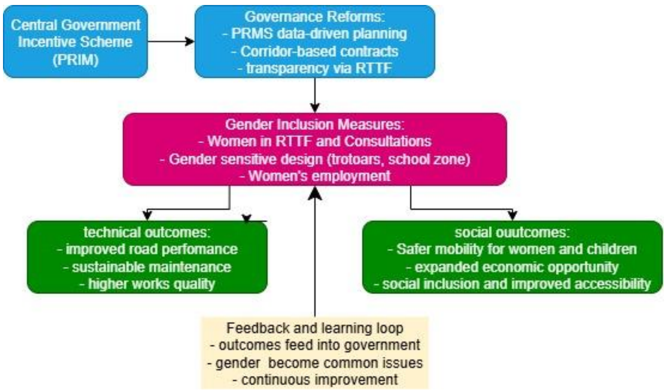

Figure 4: Feedback loop of incentive-based governance, gender inclusion, and outcomes.

4.6. Toward Gender-Responsive Governance

The experience of PRIM and RRGP shows that incentive-based programs can serve as entry points for gender-responsive governance, but more deliberate integration is needed. A gender-responsive approach would involve: (i) Formalizing women's participation in RTTFs with minimum quotas and decision-making authority, (ii) Incorporating gender-sensitive indicators into verification processes, such as representation in consultations, inclusion in contractor and consultant teams, and allocation of budget for gender-responsive design; (iii) Strengthening capacity of local governments to conduct gender audits, apply inclusive road safety assessments, and engage women's groups systematically; (iv) Embedding women-owned enterprises into procurement and maintenance systems, ensuring that economic benefits are distributed equitably. The Gender-Related Indicators and Outcomes in PRIM is shown on Table 2.

By aligning incentive-based governance mechanisms with gender equality objectives, regional road programs can simultaneously improve technical performance and advance inclusive development. This alignment is consistent with both Indonesia's policy commitments and UNDP's vision of infrastructure as a driver of equitable growth.

Table 2: Gender-Related Indicators and Outcomes in PRIM

Dimension	Indicator	Findings
Participation	Women's share in Road Transport and Traffic Forum (RTTF) consultations	10–20% of participants in some regions; often limited to advisory roles
Decision-making	Representation of women in program design & budgeting	Present but weak; women's input rarely shaped final budget/program decisions
Employment	Women employed by contractors/consultants under PRIM	7–13% of contractor staff; 7–9% of consultant staff; mainly in support roles
Community Benefits	Women's participation in roadside economic activities (food stalls, sales, services)	Increase in women-led businesses and income opportunities after road upgrades
Safety & Access	Provision of sidewalks, school-zone facilities, and drainage improvements	Slightly improved safety for women, children, and disabilities; greater access to markets and schools
Institutional Mechanisms	Gender indicators embedded in governance verification items	Initially minimal; expanded over time but remained focused on representation rather than substantive influence

5. Discussion: Proposed Framework for Incentive-Based Gender Equality Program

The experience of incentive-based programs such as the Provincial Road Improvement and Maintenance (PRIM) and the Regional Road Grant Program (RRGP) shows that well-designed fiscal incentives can drive governance reforms in Indonesia's regional road sector. These programs improved road quality, promoted transparency, and fostered participatory practices, but gender equality and social inclusion (GESI) remain underdeveloped. Women's participation has often been limited to consultation without substantive influence, while benefits have been indirect, such as improved access to markets or small-scale roadside businesses. To move beyond symbolic participation, this section outlines a Proposed Framework for an Incentive-Based Gender Equality Programme (IB-GEP) and discusses its opportunities, challenges, and implications. The framework integrates GESI indicators into governance verification, links incentives to measurable outcomes, builds institutional capacity, and establishes sustainability mechanisms.

5.1 Embedding GESI into Governance Indicators

A central lesson from PRIM and RRGP is that what gets measured and verified gets prioritized. Governance verification items—covering road asset data, procurement transparency, and programming quality—were tied to disbursement of incentives, and local governments adapted quickly to meet these requirements. Extending this logic, the IB-GEP should add GESI-focused governance indicators, such as:

- Participation quotas and influence: At least 30% representation of women in Road Transport and Traffic Forums (RTTFs) and public consultations, with evidence that their input influences final programming and budgeting.
- Employment and enterprise inclusion: Proportion of women employed by contractors and consultants; participation of women-owned small and medium enterprises (SMEs) in routine maintenance contracts.
- Gender-sensitive safety audits: Verification that project designs include sidewalks, street lighting, school-zone safety measures, and drainage systems responsive to the needs of women, children, and persons with disabilities.

- Budget allocation: Proof that a minimum share of program funds (e.g., 10%) is directed toward inclusive infrastructure facilities and GESI-related activities.

These indicators must be integrated into the verification process so that gender equality becomes a structural requirement for accessing incentive funds, not an optional add-on.

5.2 Linking Incentives to Measurable Outcomes

The effectiveness of incentive-based programs lies in their ability to create direct links between governance practices and fiscal rewards. For gender equality, the IB-GEP should establish tiered incentive levels tied to measurable outcomes: Basic compliance: Women included in RTTFs, gender-sensitive audits completed. Intermediate compliance: Women employed in project teams; inclusive design features constructed. High compliance: Evidence that women's voices shape budget allocations, women-owned enterprises participate in procurement, and measurable improvements in women's access and safety are achieved.

This graduated approach avoids tokenism by rewarding not just representation but also influence and tangible outcomes. It mirrors the incremental strengthening of governance indicators under PRIM, which expanded from four items in 2013 to over 60 by 2020 (DFAT, 2021).

5.3 Building Institutional Capacity and Ensuring Sustainability

Local governments, contractors, and consultants often lack technical expertise in gender audits, inclusive design, or participatory methods. Without capacity building, GESI indicators risk becoming check-box exercises. The framework therefore emphasizes followings: (i) Training modules on gender-responsive road governance, delivered by the Ministry of Public Works and Housing (MPWH) in partnership with universities and donors. (ii) Technical advisors embedded in local project teams to guide the integration of gender audits and inclusive design. (iii) Partnerships with women's NGOs to support consultation, monitoring, and accountability.

Gunawan et al. (2021) highlight that advisory consultants were crucial for sustaining governance reforms under PRIM; extending their role to include GESI expertise would strengthen the mainstreaming process.

Institutional sustainability is vital to prevent gender inclusion from being treated as temporary. Recommended mechanisms include: (i) Establishing Road Maintenance Management Teams (RMMTs) with explicit GESI mandates, modeled on NTB's initiative. (ii) Expanding Construction Sector Transparency (CoST) membership, requiring disaggregated reporting on women's participation and benefits. (iii) Integrating GESI into broader financing instruments such as the Specific Allocation Fund (DAK), so that gender responsiveness extends beyond PRIM/RRGP pilots to all regional road programs.

Such institutionalization ensures that gender equality is embedded in the system rather than dependent on individual projects or political will.

5.4 Opportunities and Challenges

The IB-GEP framework offers significant opportunities. First, the PRIM model has already proven that local governments adapt to incentive-driven governance requirements. Adding gender indicators builds on this momentum rather than creating new systems (Gunawan et al., 2021). Second, policy alignment. Indonesia's national frameworks—RPJMN 2020–2024, RUNK 2021–2040, and Inpres No. 9/2000 on Gender Mainstreaming—mandate gender integration, while the Sustainable Development Goals emphasize SDG 5 (gender equality) and SDG 9 (infrastructure). Embedding gender in incentive-based programs operationalizes these commitments (UNDP Indonesia, 2021). Third, catalyze transformative change. Linking fiscal incentives to gender outcomes encourages local governments to prioritize inclusivity. As PRIM shifted the culture from reconstruction to maintenance, IB-GEP could shift the culture from symbolic participation to substantive gender-responsive governance.

Despite its promise, implementing IB-GEP faces key challenges such as:

- Institutional readiness. Many local governments lack capacity to implement gender-responsive planning. Training and technical support are essential to avoid superficial compliance (DFAT, 2015).
- Risk of tokenism. Women may be present in RTTFs but lack influence. Incentives must therefore emphasize not just attendance but decision-making impact (DFAT, 2021).
- Uneven implementation. Local variations in leadership and socio-cultural contexts may lead to uneven results, as seen between NTB and Lombok Barat. Strong central monitoring and adaptive local strategies are needed.
- Complexity of monitoring. PRIM already monitored 60+ governance indicators. Adding gender indicators risks overloading local governments unless indicators are carefully selected and phased in.

International experience underscores that gender-responsive infrastructure improves both equity and governance. UNDP notes that inclusive infrastructure enhances transparency, accountability, and service delivery effectiveness (UNDP Indonesia, 2021). However, success requires systematic integration: isolated gender projects rarely achieve sustainability.

The Indonesian cases affirm this. Gender outcomes were strongest when formal requirements existed (e.g., RTTF composition, inclusion of safety facilities) and weakest where left to discretion. Institutionalized incentives, therefore, are key to lasting change.

Ultimately, IB-GEP has the potential to deliver dual dividends: more stable and sustainable roads and more equitable, inclusive development outcomes. In doing so, it strengthens Indonesia's ability to achieve national development priorities and contributes to global commitments under the SDGs.

6. Policy Recommendations

The experience of PRIM demonstrates that incentive-based programs can effectively improve governance and road service delivery in Indonesia. Building on the lessons from case studies and the proposed framework, this section explains the policy implications and recommendations necessary to promote gender-responsive incentive-based road programs.

6.1 Policy Implications and Recommendations

First, fiscal incentives can drive institutional change. The case studies show that when reimbursement is tied to governance indicators, local governments adapt their practices. This has implications for gender equality: embedding GESI indicators into incentive schemes is likely to yield stronger outcomes than stand-alone gender programs that lack financial leverage (Khan et al, 2025).

Second, governance reforms must move beyond representation. Quotas for women's participation in forums such as RTTF increased attendance, but influence on decision-making remained limited. Policy frameworks must therefore emphasize both representation and substantive influence (Han, 2015).

Third, economic opportunities for women remain underutilized. While roadside businesses expanded after road upgrades, women-owned enterprises were rarely included in formal procurement chains. This suggests a missed opportunity for mainstreaming women's economic empowerment into the road sector.

Fourth, sustainability depends on institutionalization. Temporary reforms under PRIM were more likely to endure when institutionalized—for example, NTB's Road Maintenance Management Team (RMMT) or Lombok Barat's membership in the Construction Sector Transparency (CoST) initiative. For gender equality, similar institutional mechanisms must be created to ensure that reforms are not lost after program completion.

Finally, national oversight is critical. The central government played a decisive role in monitoring and verifying PRIM and RRGP outputs. Without continued oversight, gender-responsive reforms risk being diluted at the local level. This underscores the importance of a strong multi-ministerial framework to track gender outcomes.

Based on these implications, a set of policy recommendations is presented below.

1) Embedding Gender Indicators in Governance Verification. Expand the current governance verification framework to include gender-responsive indicators, such as women's participation rates, gender-sensitive audits, and budget allocation for inclusive design. Verification teams should assess not only technical compliance but also GESI performance.
2) Ensuring Substantive Participation in Decision-Making. Mandate minimum quotas for women's representation (e.g., 30%) in RTTFs and consultation forums, and require documented evidence that women's perspectives influence final programming and budgeting decisions.
3) Expanding Employment and Economic Opportunities. Require contractors to employ women in both skilled and unskilled roles and incentivize the inclusion of women-owned SMEs in maintenance contracts. Procurement guidelines should include gender clauses to enforce these requirements.
4) Institutionalizing Gender-Sensitive Safety Audits. Introduce mandatory gender-sensitive road safety audits, with budget allocations for sidewalks, street lighting, and school-zone facilities. Verification should require evidence of implementation.
5) Establishing Sustainable Governance Structures. Formalize Road Maintenance Management Teams (RMMTs) at the provincial and district levels, with explicit mandates to oversee gender integration in planning, budgeting, and monitoring.
6) Expanding Transparency Mechanisms. Scale up Construction Sector Transparency (CoST) membership nationwide and require local governments to publish gender-disaggregated project data online.
7) Building Institutional Capacity for Gender Mainstreaming. Develop and deliver structured training modules on gender-responsive road governance, inclusive design, and participatory consultation. These should target local governments, contractors, and consultants.

6.2 Broader Implications

The integration of gender equality into incentive-based road programs carries implications beyond the road sector. It demonstrates that fiscal policy can be used as a powerful tool to mainstream social inclusion in public service delivery. By embedding gender into financial incentive structures, Indonesia can shift from symbolic gender initiatives to systemic reform. Moreover, the IB-GEP framework can serve as a model for other developing countries facing similar challenges in governance, infrastructure quality, and equity. Multi-donor agencies could replicate this approach by tying loans and grants to gender-inclusive governance indicators, thereby promoting global commitments to sustainable and equitable infrastructure (Agenor & Agenor, 2023).

7. Conclusion

This paper has examined the potential of incentive-based programs to advance gender equality and social inclusion (GESI) in Indonesia's regional road sector. Drawing on lessons from the Provincial Road Improvement and Maintenance (PRIM) program and the Regional Road Grant Program (RRGP), particularly in Nusa Tenggara Barat and Lombok Barat, the study has shown that fiscal incentives can be powerful tools for driving governance reform, improving road stability, and expanding public participation. However, while gender was included as a cross-cutting issue, its integration remained limited, often resulting in symbolic participation rather than substantive influence.

The proposed Incentive-Based Gender Equality Programme (IB-GEP) framework seeks to address these shortcomings by embedding GESI into governance verification, linking incentives to measurable outcomes, building institutional capacity, and institutionalizing sustainability mechanisms. The framework highlights the dual dividends of such an approach: improved technical performance (e.g., road performance, maintenance efficiency) and enhanced social equity (e.g., safer mobility for women and children, expanded economic opportunities for women-owned enterprises).

The policy implications and recommendations underscore that incentives should be tied directly to gender-responsive governance indicators, supported by multi-ministerial oversight, and reinforced through institutional mechanisms such as Road Maintenance Management Teams (RMMTs) and expanded Construction Sector Transparency (CoST) participation. With central government leadership and local commitment, incentive-based programs can evolve into transformative platforms for mainstreaming gender equality in infrastructure governance.

Nevertheless, this study has several limitations. First, the analysis relies primarily on secondary sources, including evaluations by DFAT (2015, 2021), Gunawan et al. (2021), and UNDP Indonesia (2021). While these documents provide rich insights, they may not fully capture on-the-ground dynamics, especially women's lived experiences in participating communities. Second, the case studies focus on NTB and Lombok Barat, which were early adopters of PRIM and may not reflect conditions in other provinces or districts with different socio-political contexts. Third, the study emphasizes governance and policy frameworks but does not include quantitative analysis of gender-disaggregated outcomes, such as changes in women's mobility patterns, income levels, or safety statistics.

Future studies could address these gaps by conducting field-based research that captures women's and marginalized groups' perspectives directly, using participatory methods and gender-disaggregated data collection. Comparative research across provinces could reveal variations in effectiveness and identify context-specific factors for success. Moreover, further studies should explore the long-term impacts of gender-responsive road governance on broader development outcomes, such as poverty reduction, labor force participation, and education access.

In conclusion, incentive-based programs have demonstrated their capacity to improve governance in Indonesia's regional road sector. With deliberate integration of gender and equality measures, these programs can also become vehicles for social transformation, helping Indonesia achieve its dual goals of infrastructure sustainability and inclusive development.

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Pandaan-Malang Toll Road Contribution as Sustainable Transport Infrastructure

Willy Hanugrah Gusti[1,*], Mohamad Agus Setiawan[1] & Filianto Nugraha Sau'[1]
*Corresponding author: willy.hanugrah@jasamarga.co.id

[1]*PT Jasa Marga (Persero) Tbk, Plaza Tol Taman Mini Indonesia Indah 13550, Jakarta, Indonesia*

ABSTRACT

Transport infrastructure such as toll roads have great influences on regional development. This paper will answer how impactful the sustainable value is from Pandaan-Malang toll road as an extension of Trans Java toll road. Pandaan-Malang toll road contribution from sustainability point of view and sustainable benefits after the toll road has been constructed and fully operated are going to be described. Data was collected from literature reviews, questionnaires and secondary data. A total of 140 participants were recruited for the primary data collection. There were 79 participants who were toll road users, 29 were arterial road users, and 32 were MSME entrepreneurs. The secondary data were collected from various resources, such as historical data from Jasa Marga and public records. The data were then analysed by using regression models. Further qualitative analysis was also performed. The regression model showed that toll road has significant impact on reduced travel time and fuel consumption. Qualitative analysis indicated that green toll road criteria was achieved by Pandaan-Malang toll road.

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1. Introduction

Social welfare could potentially be improved as transport infrastructure is being developed. The development would trigger increased economic activity alongside the region. A study showed that population also grew after huge funds were being invested in transport infrastructure (Sharma & Chandrasekhar, 2014). With easy access from rural to urban areas, workers prefer to commute to gain better employment and reduce wage differences. People would choose commuting rather than migrating due to higher property prices and rent in urban areas.

According to the National Long-Term Development Plan (2025-2045), the sixth agenda is to embody equitable and balanced regional development, and the seventh agenda is to realise quality and environmentally friendly infrastructure (Kementerian Sekretariat Negara Republik Indonesia, 2024). Both agendas call for continuing infrastructure development while maintaining the sustainability aspects. Toll road development is one example to make these agendas come true. Human mobility from one region to another would be easier, supply chain distribution would be more efficient, and economic growth would be generated positively once all the regions in Indonesia are connected by toll roads. These are the foundations to achieve Golden Indonesia by 2045.

It has been known that Java Island is the central of economic activity in Indonesia. Most of the industrial and metropolitan areas are on this island, for instance the Greater Jakarta area, Semarang, and Surabaya. During the first quarter of 2025, Gross Regional Domestic Product contribution from Java Island itself was 57,43% with year-on-year growth by 4,99% (Badan Pusat Statistik, 2025). Although the year-on-year growth was less than Sulawesi, it is safe to say that the biggest economic generator in Indonesia was from Java.

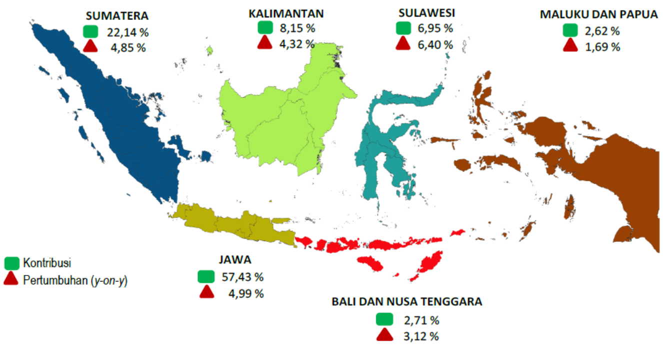


Figure 1: Indonesia's Economic Growth Infographic for Q1 2025

To maximise the economic contribution in Java Island, the Government of Indonesia has finished Trans Jawa toll road. This toll road network is claimed to successfully increase human mobility and supply chain throughout the provinces (Setijowarno, 2024). This 1.023-kilometer toll road network is stretched from Banten province to East Java province. Reduced travel time is the beneficial direct impact that public has experienced from this road network (Siswoyo, 2020). Jasa Marga as Indonesia's leading toll road development company also pointed out the importance of Pandaan-Malang toll road. It enables a more efficient route to access tourism destinations and industrial supply chain in East Java (Anwar, 2019).

This paper is going to answer a research question of how impactful the sustainable value is from Pandaan-Malang toll road. Benefit cost analysis, fuel consumption and safety comparison analysis, and environmental impact analysis are considered to evaluate toll road sustainable value. The study also describes Gross Regional Domestic Product, externality identification, travel time and vehicle breakdown data, and social benefit as secondary data for discussion. This research is projected to measure Pandaan-Malang toll road contribution from its sustainability point of view and to analyse sustainable benefits after Pandaan-Malang toll road has been constructed and fully operated.

2. Method

2.1. Study Area: Pandaan-Malang Toll Road

Pandaan-Malang Toll Road Project started out in 2017 and finished construction phase three years later to move into full operations phase by 7 April 2020. Total private investment for this project was Rp 6,359 trillion with Public Private Partnership (PPP) scheme. The project was developed by PT Jasamarga Pandaan Malang, a subsidiary of PT Jasamarga Transjawa Tol as a sub holding for Trans Jawa Toll Road in Jasa Marga group. The investment was considered large in the beginning but declined gradually. After the project had been finished, investment allocation was put into maintenance capital to preserve pavement quality. However, there will be an increase in investment, since there is going to be a lane addition plan by 2037 (LPEM FEB UI, 2024).

This project was intended to reduce travel time between Surabaya and Malang city. The 38,48-kilometer toll road connects sub-districts in Pasuruan, Malang regency, and Malang city. There are five sections of Pandaan-Malang toll road, which are Pandaan-Purwodadi (15,47 km), Purwodadi-Lawang (8,05 km), Lawang-Singosari (7,1 km), Singosari-Pakis (4,75 km), and Pakis-Malang (3,11 km) There are five interchanges and 7,06 kilometers connecting road in Pandaan-Malang toll road.

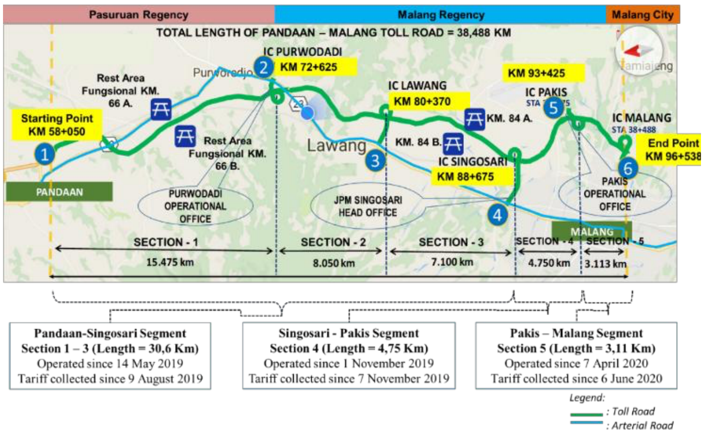


Figure 2: Pandaan-Malang Toll Road Map

2.1. Data Collection

For this paper, data was collected from literature reviews, primary data, and secondary data. There were 140 participants recruited for the primary data, 79 were toll road users, 29 were arterial road users, and 32 were MSME entrepreneurs. The participants were being interviewed with prepared questionnaires. On the other hand, secondary data obtained for this research is related to externality analysis, such as land and property prices, average daily trip via arterial road and toll road, and vehicle emission factor.

Table 1: Data Collection Method for Externality Analysis.

No	Required Data	Data Collection Method
1	Land and property prices increase	Secondary data
2	Vehicle emission factor	Secondary data
3	Monetary value of noise impact per year	Literature review, FGD
4	Productive land area converted because of toll road project	Secondary data
5	Monetary value due to urban separation	Literature review, FGD
6	Revenue before and after toll road operations	Survey, FGD

2.2. Quantitative Analysis

This research uses both quantitative and qualitative analysis. The first quantitative analysis is a regression model showing influence of toll road utility with respect to 3 main variables, fuel consumption, travel time, and breakdowns & Incidents. This model uses independent variables, such as distance in kilometers, vehicle engine capacity in CC, toll dummy (toll= 1, arterial = 0), and vehicle type dummy showing comparison with private vehicle.

$$Log\ (Travel\ Time) = \alpha + \beta_1\ (distance) + \beta_2\ (vehicle\ capacity) + \beta_3\ (toll\ dummy) + \beta_4\ (vehicle\ type) + \varepsilon \quad (1)$$

$$Log\ (Fuel\ Consumption) = \alpha + \beta_1\ (distance) + \beta_2\ (vehicle\ capacity) + \beta_3\ (toll\ dummy) + \beta_4\ (vehicle\ type) + \varepsilon \quad (2)$$

$$Breakdowns\ \&\ Incidents = \alpha + \beta_1\ (distance) + \beta_2\ (vehicle\ capacity) + \beta_3\ (toll\ dummy) + \beta_4\ (vehicle\ type) + \varepsilon \quad (3)$$

There is another quantitative analysis in this paper, which is externality analysis. It started with literature review to gain externality potential nearby Pandaan-Malang toll road project and direct impact felt by road users. After that, FGD was held with neighboring communities affected by the project, academics, and policy makers. Then, two main approaches are used to measure the externality impact, market price approach and non-market valuation. After all the data were collected, externality can be calculated and analysed.

2.3. Qualitative Analysis

To complete the quantitative analysis, this study implements qualitative analysis in the form of Green Toll Road Criteria Checklist. There are seven criteria to be checked with proof of fulfillment. The checklist can be filled in the following form.

Table 2: Green Toll Road Criteria Checklist Form.

No	Criteria	Proof of Fulfilment
1	Access, Feasibility, and Service	
2	Energy Efficiency	
3	Water Efficiency	
4	Environment	
5	Material	
6	Construction	
7	Local Partnership	

3. Results

3.1. Equations and Mathematics

Regression model estimates were shown on Table 3 for three main specifications. The first model is the travel time model with travel time logarithm as its dependent variable. The second model uses fuel consumption log as its dependent variable. Lastly, the third model is breakdowns & incidents model with total breakdowns & incidents as its dependent variable. The regression model shows that toll road utility has significant impact on travel time and fuel consumption. Toll dummy coefficient of travel time model is -0,412 meaning that travel time can be reduced by 41,2% compared to arterial road. This time efficiency is relevant for Heavy Good Vehicles having longer travel time related to private vehicles on arterial road.

Toll road utility also showed a significant decrease in fuel consumption based on the regression model. The -0,265-toll dummy coefficient indicates that fuel consumption is reduced by 26,5%. Fuel efficient travel is feasible via toll road and important for large vehicles, such as travel and van, especially on long distance trips. On the last model, toll road utility gives impact to reduction in breakdowns & incidents with a toll dummy coefficient of -0,878. This displays toll road utility relates to decrease in breakdowns & incidents frequency of 0,87 incidents. This number proves that vehicle repair costs can be reduced by using toll roads.

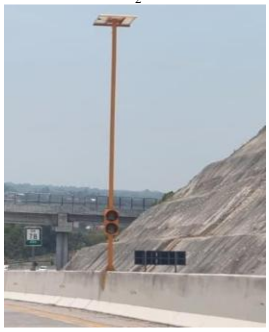
Table 3: Regression Estimates Result of Pandaan-Malang Toll Road Usage to Travel Time, Fuel Consummption, and Breakdowns & Incidents

	Statistic Coefficient		
Variable	**Ln (Travel Time)**	**Ln (Fuel Consumption)**	**Breakdowns & Incidents**
Toll	**-0,412*** **	**-0,245*** **	**-0,878** **
(1=toll | arterial)	-0,041	-0,058	-0,393
Distance	0,046***	0,038***	0,026
	-0,004	-0,006	-0,033
Vehicle CC	0,000***	-0,245***	0
	0	-0,058	0
Bus	-0,021	0,109	-1,623
(1=bus | private)	-0,087	-0,311	-1,319
Truk	0,288***	0,025	0,009
(1=truk | private)	-0,077	-0,158	-1,154
Travel	0,373***	0,388***	-0,76
(1=travel | private)	-0,106	-0,148	-0,492
Van	0,212***	0,037	-0,486
(1=van | private)	-0,068	-0,165	-0,493
Constants	1,824***	-0,338	0,038
	-0,156	-0,236	-1,322
Observation	210	201	210

Robust standard errors in parentheses
*** p<0,01 (significant on 99% confidence level), ** p<0,05 (significant on 95% confidence level), and * p<0,1 (significant on 90% confidence level)

Regarding qualitative analysis, there were seven criteria to be checked to classify Pandaan-Malang toll road as a Green Toll Road. While these criteria can be fulfilled by most toll roads, Pandaan-Malang toll road has its own uniqueness. For instance, carbon absorbing-tree planting programs to reduce CO2 emission and roadside plants height maintenance can work side-by-side to check access, feasibility, and service criterion and environment criterion. Energy efficiency criterion was satisfied by solar cell street lighting and solar cell warning light implementation. Surface water reservoir and water recycling for ablution checked the water efficiency criterion. Pandaan-Malang toll road also used eco green material and green building concept for its Head Office, so that material and construction criteria were checked. Finally, a local partnership with local police and Department of Transport for regular Over Dimension and Overload law enforcement checked the box for the last criterion.

Table 4: Green Toll Road Criteria Checklist Realisation

No	**Criteria**	**Proof of Fulfilment**
1	Access, Feasibility, and Service	 Carbon Absorbing-Trees Planting Program to reduce CO_2 Emission
2	Energy Efficiency	 Solar Cell Street Lighting
3	Water Efficiency	 Surface Water Reservoir
4	Environment	 Roadside plants do not exceed cables height
5	Material	 Eco green material

No	Criteria	Proof of Fulfilment
6	Construction	 Green Building
7	Local Partnership	 Over Dimension Overload Law Enforcement with local police

4. Discussion

In terms of externality analysis, Pandaan-Malang Toll Road has a substantial positive externality with a value of Rp 395,6 billion per year. There are two indicators of this externality, vehicle emission reduction and land prices increase. Vehicle emission reduction only contributes as big as Rp 4,65 billion per year. But then, land prices increase gives a lot more contribution to this externality with Rp 390,95 billion per year. This shows positive impact towards the environment due to lower fuel consumption. Moreover, it is safe to say that property value increase in the surrounding area is highly influenced by Pandaan-Malang toll road.

Nevertheless, this toll road has a considerable amount of negative externality. The largest impact came from economic decline on arterial roads with a value of Rp 321,91 per year. Next contributor is noise with Rp 34,4 billion per year, urban areas separation with Rp 18,69 billion per year, and land use change with Rp 11,33 billion per year. This indicated traffic flow shifting to toll road distresses MSME activity reduction on arterial road.

Overall, the positive benefits of Pandaan-Malang Toll Road are superior to its negative impacts proven by net externality of Rp 9,27 billion per year. Yet, noise management and MSME support should be executed to ensure toll road benefits reach all relevant parties as mitigation efforts.

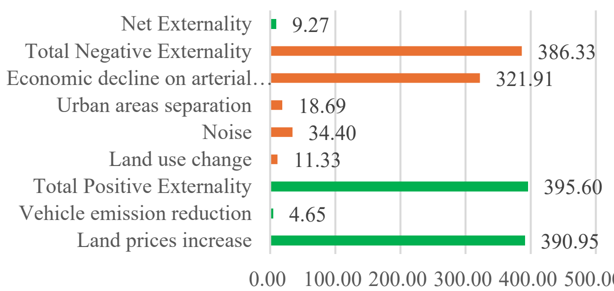


Figure 2: Average Externality Value Estimates per Year on Pandaan-Malang Toll Road

Knowing that Pandaan-Malang Toll Road has been fully operated since 2020, average land and property tax receipt from the year 2016-2020 to 2021-2023 on all regions increased by 42%. There was also a significant rise of 55% when average land and property tax receipt on all regions was compared between the year 2020 and 2023. This means that Pandaan-Malang toll road connectivity influenced land and property prices on regions passed by the toll road. The affected regions were Malang Regency, Pasuruan Regency, and Malang City. Property growth in industrial, residential, and commercial area is potentially triggered by Pandaan-Malang toll road presence.

All three regions in Malang Regency, Pasuruan Regency, and Malang City showed an upward trend of land and property tax receipt. Over the last 8 years, there was a dramatic rise from Rp 60 billion in 2016 to Rp 140 billion in 2023 for Malang Regency. On the other hand, Pasuruan Regency experienced a less significant increase from Rp 50 billion in 2016 to Rp 97 billion in 2022. However, the land and property tax receipt of Pasuruan Regency fell to Rp 86 billion in 2023. Finally, there was also a rise in tax receipts in Malang city from Rp 62 billion in 2016 to Rp 90 billion in 2023. To sum up, there was a positive correlation between fully operated Pandaan-Malang toll road with land and property tax receipt increase in Malang Regency and Malang City, but not in Pasuruan regency.

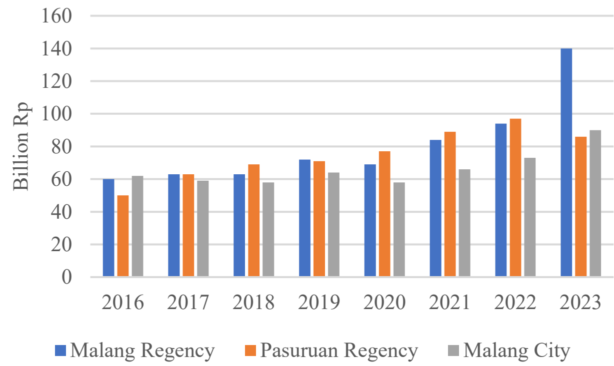


Figure 3: Property Tax Receipt in Malang Regency, Pasuruan Regency, and Malang City for 2016-2023 period

5. Conclusion and Recommendations

It can be concluded that Pandaan-Malang toll road gave significant impact on reduced travel time and fuel consumption. In terms of travel time, driving on Pandaan-Malang toll road only took 26,5 minutes related to 47,3 minutes on arterial road, almost two times faster. Fuel consumption while using Pandaan-Malang toll road also decreased by 29% compared to arterial road, making toll road choice more energy efficient. Other data also showed that Pandaan-Malang toll road is almost two times safer than arterial road with less probability of vehicle breakdowns and incidents (1,09 occurrence per year on toll road).

Pandaan-Malang toll road had successfully checked all the Green Toll Road criteria. This is also proven by Green Toll Road Gold plus level certification by Green Infrastructure and Facilities Indonesia in 2023 and in 2020. This remarkable award confirmed the toll road to be sustainable. Other than that, Pandaan-Malang toll road also promotes sustainable tourism via ease of access to reach Bromo Mountain and other tourism destinations, endorses Micro, Small, and Medium Enterprises (MSME), and enables rest area waste management.

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Application of Pavement Maintenance Strategies for Highways

Chun-Hsiung Hsieh [1], Chieh-Chih Chang [2], Chiung-Fu Kuo [3], Chun-Hung Kuo [4], Shih-Huang Chen [5] & Li-Ling Huang [6,*]
*Corresponding author: irenahf@gmail.com

[1]*Director, Northern Region Branch Office, Highway Bureau, MOTC, Taipei, Taiwan*
[2]*Chief, Jingmei Branch, Northern Region Branch Office, Highway Bureau, MOTC, Taipei, Taiwan*
[3]*Engineer, Jingmei Branch, Northern Region Branch Office, Highway Bureau, MOTC, Taipei, Taiwan*
[4]*Technical Manager, Deyuan Construction LTD. , New Taipei, Taiwan*
[5] *Professor, Department of Civil Engineering, National Central University, Taoyuan, Taiwan*
[6] *Ph.D. Candidate, Department of Civil Engineering, National Central University, Taoyuan, Taiwan*

ABSTRACT

With advances in technology, highway maintenance has gradually shifted from traditional manual inspection to intelligent survey methods. This study focused on Taiwan Provincial Highway No. 2 along the North Coast, where intelligent detection devices were introduced to investigate pavement conditions. By integrating cloud-based AI recognition, the system enabled rapid and efficient pavement distress surveys, providing advantages over traditional manual approaches in terms of higher efficiency, lower cost, improved data objectivity, and enhanced worker safety. The indicator-based analysis further served as a reliable foundation for subsequent maintenance decision-making.

For minor distresses such as cracks, low-severity alligator cracking, and potholes, preventive maintenance techniques were implemented to extend pavement service life and reduce the need for large-scale milling and resurfacing. This approach achieved an annual carbon reduction of approximately 18,834 kgCO$_2$e. For more severe distresses including rutting, settlement, and extensive continuous damage, localized repairs or full-depth milling and overlay were adopted. Sustainable concepts were incorporated by applying eco-friendly materials and innovative construction methods, such as dual-machine paving using advanced milling and paving equipment, which improved smoothness and joint quality. Field applications demonstrated a reduction in International Roughness Index (IRI) from 4.0 to 1.74. By improving pavement smoothness, fuel consumption was reduced, yielding an average annual carbon reduction of about 25.1 tons per kilometer.

This paper establishes a highway maintenance decision-making model centered on intelligent inspection, sustainable materials, and sustainable highway practices. The approach simultaneously achieves quality enhancement, efficiency improvement, and carbon reduction. The North Coast Highway maintenance project has been recognized with multiple honors, including the 2024 Taiwan National Sustainable Development Award, the 2025 REAAA MINO Award, the 5th TSAA Taiwan Sustainability Action Award, and the 4th APSAA Asia-Pacific Sustainability Action Award.

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Sustainable materials
Sustainable highway

1. Introduction

1.1 Research Background

With the increasing service demand of provincial highways and the continuous growth of traffic loads, pavement deterioration has become a pressing issue, manifesting in forms such as cracking, alligator cracking, potholes, and rutting. Selecting the most appropriate maintenance materials and methods for different types of damage is not only essential to ensuring driving safety and service quality but also critical to enhancing the efficiency and effectiveness of maintenance resource allocation. Therefore, this study aims to develop pavement maintenance strategies tailored to specific distress types, thereby improving the distribution of maintenance resources and extending roadway service life.

For the investigation process, intelligent detection devices were employed to conduct pavement surveys, offering advantages of high efficiency, low cost, and enhanced safety compared with traditional manual inspection. In terms of maintenance practices, this study emphasizes preventive maintenance as well as the adoption of sustainable materials and construction methods. For relatively minor distresses such as cracks, low-severity alligator cracking, and potholes, preventive treatments including asphalt sealant, asphalt membrane, surface sealing, and asphalt bricks were applied. For more severe distresses such as rutting, settlement, and extensive continuous damage, full-depth milling and overlay were adopted, incorporating advanced milling and paving machines along with Warm Mix Asphalt (WMA) to ensure both construction quality and carbon reduction benefits.

1.2 Research Objectives

The objectives of this study are as follows:

- Intelligent investigation and decision-making: To conduct pavement surveys using intelligent detection devices and establish a maintenance decision-making framework based on the survey results, thereby improving objectivity and efficiency in resource allocation.
- Evaluation of materials and methods: To propose appropriate maintenance techniques—such as asphalt sealant, asphalt membrane, surface sealing, asphalt bricks, and full-depth milling and overlay—based on different distress types, and to establish standardized construction procedures.
- Benefit assessment: To quantify the performance of different materials and construction methods in terms of smoothness (International Roughness Index, IRI), CO_2 emissions, and cost, providing a reference for future maintenance resource allocation.

1.3 Methodology Framework

This study adopts a systematic methodology integrating intelligent inspection, condition analysis, maintenance strategy selection, and sustainability evaluation. The overall research framework is illustrated as follows:

- Intelligent inspection: A smartphone-based pavement inspection system combined with cloud-based AI recognition was employed to collect and analyze pavement condition data, including cracking, rutting, potholes, and International Roughness Index (IRI).
- Pavement condition analysis: Based on the inspection results, pavement distresses were classified into different categories and severity levels, forming the basis for maintenance decision-making.
- Maintenance strategy selection: Appropriate maintenance treatments were selected according to distress types, including preventive maintenance (crack sealing, asphalt membrane, surface sealing, and asphalt bricks) and corrective maintenance (localized repair and full-depth milling and overlay).
- Sustainable construction application: Advanced construction technologies and materials, such as small-scale milling and paving equipment and Warm Mix Asphalt (WMA), were implemented to enhance construction quality and reduce environmental impacts.
- Sustainability and performance evaluation: The effectiveness of the proposed strategies was evaluated using performance indicators including IRI improvement, carbon emission reduction, and energy consumption. Carbon emissions were calculated based on emission factors from recognized databases.
- Through this structured approach, the study establishes a comprehensive pavement maintenance decision-making model that integrates engineering performance and sustainability considerations.

2. Intelligent Inspection and Pavement Condition Analysis

According to domestic and international literature, intelligent inspection technologies can significantly improve efficiency, reduce costs, and enhance safety (Allen A. Zhang et al., 2024; Li-Ling Huang et al., 2024). Therefore, the North Coast Highway (Provincial Highway No. 2) first adopted a novel smartphone-based detection system to survey pavement conditions. Based on the results, corresponding maintenance strategies were developed (Li-Ling Huang et al., 2025), with representative deteriorated sections selected as the study areas to evaluate the effectiveness of different maintenance materials.

2.1 Intelligent Detection Devices

2.1.1 Intelligent Inspection System

The system consists of three main components: the mobile terminal, cloud-based AI computing, and back-end management. A smartphone is mounted on the windshield inside a vehicle using a suction cup or clamp, with the camera kept level and free from wiper or glare interference.

After inspection, images and sensor data are uploaded to the cloud, where the system automatically recognizes and analyzes pavement distresses, including cracks, rutting, International Roughness Index (IRI), potholes, and level differences, following the methods specified by the Japan Road Association (2019). Results are visualized on a map, typically in 10 m intervals, and inspection reports are generated to support maintenance planning.

Using this system on the North Coast Highway, pavement inspection was carried out as shown in Figure 1. Compared with traditional manual surveys, the intelligent system reduces time and labor costs.

Figure 1: Intelligent pavement inspection device

2.1.3 Comparison with Traditional Inspection

- Cost: Intelligent inspection requires less manpower and time than manual inspection, effectively lowering costs.
- Efficiency: Unlike visual surveys, the system allows a single vehicle and operator to conduct inspections under normal traffic conditions, with cloud computing providing rapid analysis results.
- Effectiveness: Automated recognition and analysis ensure greater objectivity compared with manual evaluations.
- Safety: Inspections are completed from inside the vehicle, reducing on-road measurements and lane occupancy, thereby lowering personnel risks.

2.2 Pavement Condition Analysis

Based on the intelligent inspection results, the North Coast Highway was found to be primarily affected by cracking and alligator cracking, accompanied by localized rutting, potholes, and settlement. The following subsections provide detailed evaluations of each distress type.

2.2.1 Cracking

Longitudinal cracks in asphalt concrete typically include fatigue cracks, rutting cracks, and construction joint cracks. Fatigue cracks commonly occur within wheel paths, initiated by tensile strain and stress at the bottom of the surface layer under repeated traffic loads, propagating upward to the surface. Rutting cracks are also fatigue-related, forming as longitudinal lines along wheel tracks, often in high-temperature and heavy-traffic sections, propagating downward from the surface. Construction joint cracks occur at joints or interfaces due to insufficient bonding. Transverse cracks, most notably reflection cracks, are often observed when the underlying layer consists of concrete or asphalt overlays, propagating upward into the surface layer.

2.2.2 Alligator Cracking

Alligator cracking commonly develops along wheel paths. Once cracks penetrate, rainwater infiltrates into lower layers or the subgrade, reducing structural strength due to increased moisture and accelerating the spread of linear cracks into block cracking. In addition to fatigue loading, insufficient bearing capacity of the base or subgrade is also a major cause. Alligator cracking can be categorized into low- and high-severity levels, with tailored maintenance strategies developed to optimize resource allocation.

2.2.3 Potholes

Potholes are among the most common pavement distresses, caused by structural weaknesses, rainfall, and traffic loading. Water infiltrating through cracks accelerates their formation.

The most common repair method is patching with cold-mix asphalt concrete (Jian-Shiuh Chen et al., 2011). The repair procedure includes:

- Cleaning loose aggregates and debris.
- Applying tack coat uniformly at the bottom and edges.
- Placing and leveling cold-mix asphalt or high-performance cold-mix asphalt, leaving the repair slightly above the existing surface to prevent post-compaction settlement.
- Compacting with a vibratory plate compactor to achieve proper density and leveling.

2.2.4 Rutting and Settlement

Rutting refers to continuous depressions in wheel paths along the direction of traffic, while settlement generally occurs with block cracking as localized subsidence. Causes include design deficiencies, poor construction practices, material problems, and high traffic loading. Common contributors are high summer temperatures, a high proportion of heavy vehicles, or concentrated loads at intersections.

2.2.5 Pavement Maintenance Strategies

- Cracks: Preventive maintenance using asphalt sealants has been recommended (Wei-Hao Min et al., 2025) to prevent further water infiltration and progressive deterioration, thereby extending pavement service life and reducing the need for large-scale reconstruction.
- Alligator cracking: For low-severity cracking, asphalt membranes and surface sealing are applied to prevent further deterioration. For high-severity cracking, localized small-area repairs are used instead of large-scale rehabilitation to optimize resource utilization.
- Potholes: Although cold-mix asphalt is commonly used, its durability typically lasts only 1–3 months and negatively impacts riding comfort. To address this, asphalt bricks have been introduced (Ming-Ze Hong et al., 2020), enhancing both durability and comfort of pothole repairs.
- Rutting, settlement, and extensive continuous damage: Full-depth milling and asphalt concrete overlay are adopted. To enhance quality and sustainability, innovative materials and equipment are employed, including Warm Mix Asphalt (WMA), advanced milling machines, and modern paving equipment.

3. Preventive Maintenance Practices

3.1 Crack Sealing

Crack sealing is a key technique in preventive pavement maintenance, primarily aimed at filling cracks on the road surface to prevent water infiltration into the base and thereby extend pavement service life. The following summarizes important construction considerations, procedures, and maintenance methods:

- Construction considerations
  - Cracks must be cleaned of dust, gravel, and debris to ensure proper adhesion of sealing materials.
  - Appropriate sealant materials should be selected to ensure strong bonding under varying temperatures and traffic loads.
  - The sealant should be heated to the recommended range of 160–180 °C to maintain adequate flowability and adhesion.
- 2. Construction procedure
  - Cleaning: Compressed air is used to blow dust and debris from cracks, ensuring a dry and clean surface.
  - Filling: Heated sealant is poured into cracks and compacted to ensure full penetration.
  - Leveling: Excess material is leveled with the pavement surface to prevent unevenness.

Figure 2: Example of crack sealing

3.2 Asphalt Membrane

For low-severity alligator cracking, asphalt membranes are applied as a preventive treatment. The membrane acts as a barrier, preventing crack propagation and water infiltration, thereby extending service life.

- Construction considerations
  - Damaged areas must be thoroughly cleaned before installation.
  - If depressions exist, they should be leveled using cold-mix asphalt or other materials before applying the membrane.
  - Construction should not be conducted under wet conditions to avoid bonding failure.
- Construction procedure
  - Clean and dry the cracked area.
  - Place asphalt membrane over the cracks, ensuring tight adhesion.
  - Lightly hammer the membrane surface to enhance bonding with the pavement.

Figure 3: Example of asphalt membrane application

3.3 Surface Sealing

For low-severity cracking or minor potholes and settlements, surface sealing is another preventive method. This technique prevents further deterioration, maintains surface waterproofing, and improves riding comfort. Depending on the need, polymer-modified asphalt sand, hot-mix asphalt concrete, or polymer-modified emulsified asphalt can be applied.

- Construction considerations
  - Suitable only for surface-layer maintenance; insufficient subgrade strength should be reinforced beforehand.
  - Construction is prohibited when rain is forecast within 24 hours or during curing.
  - Hot-mix asphalt sealing should not be applied when temperatures are below 10 °C or surfaces are wet.
- Construction procedure
  - Spray emulsified asphalt tack coat.
  - Fill depressions or potholes with cold-mix asphalt if necessary.

- ➢ Apply the chosen sealing material uniformly over the pavement.
- ➢ Compact and allow to cure before reopening to traffic.

Figure 4: Example of surface sealing

3.4 Asphalt Bricks

For pothole repair, conventional cold-mix asphalt is commonly used, but its durability typically lasts only 1–3 months, adversely affecting ride quality. To enhance performance, asphalt bricks were introduced in this study. Manufactured to standardized dimensions, asphalt bricks are installed with cement, ferric oxide, and water as jointing materials. This method improves both durability and comfort.

- Construction considerations
  - ➢ Standard asphalt bricks are circular with a 40 cm diameter and 5 cm thickness; repair areas must match this dimension.
  - ➢ Cement–ferric oxide–water mixtures must be prepared as bonding materials to ensure adequate adhesion with existing pavement.
  - ➢ Construction should be avoided in rainy conditions; if water enters the drilled hole, it must be removed before installation.
- Construction procedure
  - ➢ Core the damaged pavement area to a 40 cm diameter and 5 cm depth.
  - ➢ Clean and dry the cored hole.
  - ➢ Place jointing materials in the hole.
  - ➢ Install the asphalt brick and compact to finish.

Figure 5: Example of asphalt brick application

3.5 Evaluation of Preventive Maintenance Benefits

The purpose of preventive maintenance is not only to delay pavement deterioration but also to improve resource utilization efficiency and environmental sustainability. This study introduced diverse preventive measures—including crack sealing, asphalt membranes, surface sealing, and asphalt bricks—aimed at enhancing road service quality while delivering sustainability benefits (Chun-Yao Chen, 2023).

Carbon reduction was estimated using carbon footprint coefficients published by the Ministry of Environment, Taiwan (MOENV, 2024). The database is developed based on internationally recognized methodologies, including the IPCC Guidelines for National Greenhouse Gas Inventories.The emission factor of asphalt concrete was taken as 129 kgCO_2e/t according to the official carbon footprint database.

The calculation is shown in Equation (1), where the emission factor of asphalt concrete is 129 kgCO_2e/t. By applying preventive maintenance on the North Coast Highway, large-scale milling and resurfacing were avoided, reducing asphalt concrete usage by approximately 146 t annually. This results in an estimated carbon reduction of 18,834 kgCO_2e per year.

$$\text{Carbon Reduction (kgCO2e)} = \text{Reduction in Asphalt Concrete (t)} \times \text{Emission Factor (kgCO2e/t)} \quad (1)$$

4. Application of Sustainable Construction and Materials

4.1 Application of Equipment for Small-Scale Milling and Paving

Traditional small-area rectangular patching techniques often encounter issues such as uneven paving, tack coat contamination, and poor durability. To address these problems, this study proposes an enhanced method for small-scale repairs aimed at improving the quality of localized pavement restoration. This approach was applied to provincial highways, particularly in areas with severe alligator cracking or repeatedly patched potholes. The method offers a more effective maintenance solution, reducing the frequency of large-scale rehabilitation, lowering maintenance costs, and improving both riding comfort and safety.

Construction procedure:

- Marking and cutting: The damaged area is delineated and cut into a rectangular shape using a saw cutter. Ensuring clean edges enhances bonding between the patch and existing pavement.
- Milling: A mini-milling machine is used to remove the damaged pavement to the required depth. Unlike conventional methods, the machine allows transverse milling, reducing the need for manual trimming and ensuring neat patch edges.
- Cleaning and tack coat application: The milled area is cleaned with a sweeper, followed by uniform tack coat spraying to improve adhesion. Special care is taken to maintain a clean surface.
- Paving: A handheld paver is used to place hot-mix asphalt concrete (HMA), with adjustable paving widths as small as 25 cm, making it suitable for localized repairs. Two machines operating alternately can further improve efficiency.
- Compaction: A small roller compacts the patch to ensure smoothness and durability.
- Reopening to traffic: The repaired section is opened once the surface temperature falls below 50 °C.

Figure 6: Example of small-scale repair

4.2 Application of Advanced Milling and Paving Equipment

A multifunctional milling machine was employed to ensure a smooth milled surface. Machines with laterally movable drums were also used, enabling efficient milling in areas with varying widths.

For paving, an asphalt paver equipped with ultrasonic sensors and a long screed beam was used to enhance surface smoothness. Additionally, an automatic tack coat distributor was applied to prevent contamination from tire pick-up and improve pavement durability.

The latest crawler-type multifunctional paver was also introduced, with four major features:

- Sustainability: Equipped with a high-efficiency diesel engine operating at low RPM to reduce fuel consumption, noise, and emissions. Energy-saving devices further reduce fuel usage and emissions, aligning with sustainable construction goals.
- Paving management: Advanced conveying systems ensure stable material flow and uniform distribution even under variable paving widths, improving quality.
- Operating system: The machine includes an intuitive touchscreen interface, modular settings, and lighting for improved precision, convenience, and safety during nighttime operations.
- Automation: Automatic elevation and slope control systems ensure pavement smoothness. Automated joint-matching functions provide accurate steering and width control, producing high-quality longitudinal joints.

For example, when paving two lanes along Provincial Highway No. 2, the first lane was completed conventionally, while the second lane used the crawler-type paver's automatic joint-matching system to create a hot joint with the first lane. This eliminated the need for manual joint treatment and improved joint quality. The automated elevation and slope control further enhanced surface smoothness and service quality.

Figure 7: Example of advanced paving equipment

4.3 Application of Warm Mix Asphalt Concrete (WMA)

Warm Mix Asphalt (WMA) technology was applied for the first time on provincial highways. From the mix design stage in the laboratory to field implementation, WMA performance was ensured to meet construction standards. Trial paving compared WMA with conventional Hot Mix Asphalt (HMA).

- Placement temperature: HMA ~144 °C; WMA ~126 °C.
- Compaction temperatures:
  - HMA: Initial ~116 °C; Intermediate ~94 °C; Final ~69 °C
  - WMA: Initial ~96 °C; Intermediate ~78 °C; Final ~55 °C

These results confirmed that WMA reduced working temperatures by approximately 20 °C, achieving the intended energy-saving benefit.

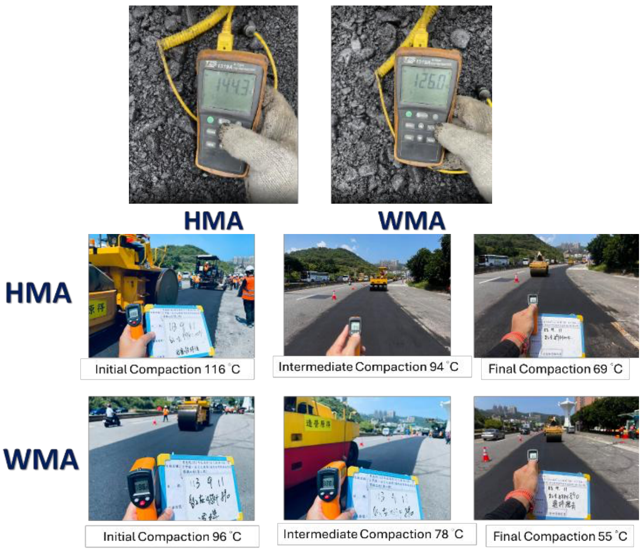

Figure 8: Field paving temperatures of HMA and WMA

4.4 Evaluation of Sustainability Benefits

The integration of sustainable equipment, small-scale milling/paving, and WMA aimed to balance road service quality with environmental sustainability. These innovations not only improved maintenance efficiency but also achieved measurable carbon reduction.

In a 2023 project, the International Roughness Index (IRI) was reduced from 4.0 to 1.74, an improvement of over 50%, comparable to expressway standards. International studies indicate that fuel consumption of passenger cars is highly correlated with IRI. Greenhouse gas emissions were calculated in accordance with the Guidelines for Greenhouse Gas Inventory published by the Ministry of Environment, Taiwan (MOENV, 2024). According to the same source, each liter of gasoline emits approximately 2.36 kg CO_2. A decrease of one IRI corresponds to a reduction of ~0.45 kg CO_2 per 100 km. In this case, the improved smoothness reduced ~1.02 kg CO_2 per 100 km per vehicle. Given an average daily traffic of 6,754 cars, this equates to an annual reduction of ~25.1 tons of CO_2 per kilometer.

Warm Mix Asphalt (WMA) achieves energy savings and carbon reduction primarily by lowering the production temperature at asphalt mixing plants, thereby reducing natural gas consumption. In this study, the environmental benefits of WMA were preliminarily evaluated based on the reduction in natural gas usage during production.

Field measurements were conducted at the asphalt mixing plant during trial paving. The average natural gas consumption rate for Hot Mix Asphalt (HMA) production was approximately 682 m³/hr, whereas that for WMA production was reduced to approximately 528 m³/hr.

Greenhouse gas (GHG) emissions were calculated in accordance with the Guidelines for Greenhouse Gas Inventory published by the Ministry of Environment, Taiwan (MOENV, 2024). The calculation method is expressed in Equation (2):

$$\text{GHG Emissions } (\text{kgCO}_2\text{e}) = \text{Natural Gas Consumption } (\text{m}^3) \times \text{Emission Factor } (\text{kgCO}_2\text{e/TJ}) \times \text{Conversion Factor} \times \text{Lower Heating Value } (\text{kcal/m}^3) \times \text{Global Warming Potential} \quad (2)$$

The conversion factor was 4.1868×10^{-9} (TJ/kcal), and the lower heating value of natural gas was taken as 8,845 kcal/m³. The emission factors and global warming potentials (GWP) for CO_2, CH_4, and N_2O were adopted according to the MOENV guidelines.

Based on the calculation results, the GHG emissions from natural gas consumption during HMA production were approximately 1,418 $kgCO_2e$/hr, while those for WMA production were approximately 1,098 $kgCO_2e$/hr. With an average production rate of 80 tons per hour, the emissions per ton of asphalt mixture were estimated as follows:

- HMA: approximately 17.7 $kgCO_2e$/t
- WMA: approximately 13.7 $kgCO_2e$/t

These results indicate that, considering only natural gas consumption, WMA reduces greenhouse gas emissions by approximately 23% compared with HMA. This demonstrates that WMA is effective in reducing energy consumption and achieving carbon reduction benefits during asphalt production.

5. Discussion

The sustainability benefits of milling and paving strategies were evaluated from both material consumption and operational perspectives. Compared with traditional large-scale rehabilitation, the use of small-scale milling and localized paving significantly reduces the volume of removed and newly produced asphalt materials. This directly contributes to lower material consumption, reduced transportation demand, and decreased energy use during construction.

In addition, the integration of advanced milling equipment and automated paving systems improves construction precision and surface quality. The improved pavement smoothness, as reflected by the reduction in IRI from 4.0 to 1.74, not only enhances riding comfort but also leads to indirect environmental benefits through reduced vehicle fuel consumption and associated carbon emissions.

From a carbon emission perspective, preventive maintenance and localized repair strategies reduce the need for full-depth milling and overlay, thereby minimizing high-energy processes and material production. Furthermore, the application of Warm Mix Asphalt (WMA) lowers production temperatures and reduces fuel consumption at asphalt plants, resulting in significant greenhouse gas emission reductions.

To further quantify the carbon reduction benefits, this study evaluates emissions across multiple stages, including material production, construction processes, and operational performance. The results are summarized in Table 1.

Table 1: Carbon emission reduction benefits of pavement maintenance strategies.

Category	Description	Reduction Value
Material reduction	Preventive maintenance reduced asphalt concrete usage by 146 tons/year	18,834 $kgCO_2e$/year
Production emissions	HMA: 17.7 $kgCO_2e$/t; WMA: 13.7 $kgCO_2e$/t	23% reduction
Operation stage	IRI improved from 4.0 → 1.74, reducing vehicle fuel consumption	25.1 tons CO_2/km/year

6. Conclusion and Recommendations

This study demonstrates that the integration of intelligent inspection, preventive maintenance, and sustainable construction technologies can significantly enhance both pavement performance and environmental sustainability in highway maintenance.

This study applied intelligent inspection devices on Provincial Highway No. 2 (North Coast), enabling rapid, objective, and low-risk pavement surveys. Distresses such as cracking, alligator cracking, potholes, and rutting were effectively identified. Compared with traditional manual surveys, the system demonstrated advantages in terms of higher efficiency, lower costs, improved data objectivity, and enhanced worker safety, providing a reliable basis for maintenance decision-making.

For preventive maintenance, multiple techniques, including crack sealing, asphalt membranes, surface sealing, and asphalt bricks, were implemented. These measures reduced asphalt concrete consumption by approximately 146 tons per year, corresponding to an annual carbon reduction of about 18,834 $kgCO_2e$, demonstrating the effectiveness of preventive strategies in reducing resource consumption and environmental impact.

In terms of sustainable construction, the adoption of enhanced small-scale repair methods, advanced milling machines, and modern paving equipment significantly improved pavement quality and safety. Field applications showed a reduction in the International Roughness Index (IRI) from 4.0 to 1.74, representing an improvement exceeding 50% and approaching expressway standards. The improved pavement smoothness further reduced vehicle fuel consumption, achieving an estimated annual carbon reduction of approximately 25.1 tons CO_2 per kilometer.

Regarding sustainable materials, Warm Mix Asphalt (WMA) was successfully introduced on provincial highways. Compared with conventional Hot Mix Asphalt (HMA), WMA reduced production and compaction temperatures by approximately 20–25 °C, thereby improving working conditions while lowering energy consumption and greenhouse gas emissions. The results indicate that WMA can reduce CO_2 emissions by approximately 20–25%, confirming its effectiveness as a low-carbon paving material.

From a practical perspective, the proposed approach provides a structured framework for highway agencies to optimize maintenance strategies by integrating intelligent inspection data with sustainability-oriented decision-making. The findings support the transition from traditional reactive maintenance to preventive and performance-based maintenance practices.

For future implementation, it is recommended that intelligent inspection technologies be adopted as standard tools for pavement management systems, enabling real-time monitoring and data-driven decision-making. In addition, the wider application of WMA and localized repair techniques should be promoted to further reduce carbon emissions and improve resource efficiency.

From a strategic perspective, highway maintenance should incorporate sustainability indicators—such as carbon emissions, energy consumption, and material usage—into decision-making processes. By doing so, agencies can achieve long-term environmental, economic, and operational benefits, contributing to the development of low-carbon and sustainable transportation infrastructure.

The proposed improvements have demonstrated significant sustainability outcomes. The North Coast Highway maintenance project received the 2024 Taiwan National Sustainable Development Award and was further recognized in 2025 with the REAAA MINO Award, the 5th Taiwan Sustainability Action Award (TSAA) – Outstanding Award, and the 4th Asia-Pacific Sustainability Action Award (APSAA) – Silver Award. These achievements highlight both national and international recognition, confirming the applicability and value of this research in advancing sustainable highway maintenance practices.

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Factors associated with road fatalities along roads with Non-Exclusive Motorcycle Lanes (NEMCL)

Muhammad Marizwan Abdul Manan[1,*], Rohayu Sarani[1] & Zamira Hassanah Zamzuri[2]
*Corresponding author: marizwan@miros.gov.my

[1] *Malaysian Institute of Road Safety Research, 43000 Kajang, Selangor, Malaysia*
[2] *Universiti Kebangsaan Malaysia (UKM), 43600 Bangi, Selangor, Malaysia*

ABSTRACT

The Non-Exclusive Motorcycle Lanes (NEMCL) were built to curb the rising of motorcycle fatalities in Malaysia. Nonetheless, motorcycle fatalities on roads equipped with NEMCL are still present, which road authorities question its reliability. This study examines the causality and probability of road fatalities along roads with and without NEMCL. This study utilizes crash data from police, road environment data and geospatial data, which are based on selected Federal Roads with NEMCL in Peninsular Malaysia, to analyze four out-comes: (1) Fatal crash cases on road with NEMCL, (2) Fatal crash cases on road without NEMCL, (3) non-fatal crash cases on road with NEMCL and (4) non-fatal crash cases on road without NEMCL. This study uses a machine learning algorithm approach, i.e., the Bayesian network analysis, by which the structure of the data was studied, and the relationship was estimated through conditional probability based on the Bayes' theorem. The Bayesian network computed that single or dual carriageway roads with NEMCL, equipped with adequate lane width for NEMCL have an even lower probability of fatal crash, ranges from 0.2% to 1.7%. The network al-so predicted up to 18.4% chance of fatal crash to occur if roads are not equipped with NEMCL, and for a typical rural road along four-lanes single carriageway, the probability of fatal crash cases occurring is more than twenty times the risk if it is not equipped with NEMCL. The use of the Bayesian network creates probability estimates to enable the identification of risk, and the necessary precautions needed to be implemented.

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1. Introduction

The effect of the increasing popularity of motorcycles has brought up issues on road safety. Analysis from Abdul Manan and Várhelyi (2012) reveals that Malaysia still holds the record for having one of the highest road fatalities per 100,000 population in ASEAN countries. After the Covid Pandemic period in 2020, Malaysia fatalities has increase to 6,080 death (see Figure 1) Based on Fig. 1, Malaysian motorcyclists fatality rates have increase steadily over the past 10 years, from 60.4% in 2012 to 68.6% in 2021 (PDRM 2010, 2012, 2014, 2021). Moreover, this data shows that by the end of year 2022, the death ratio of motorcyclists has become 2:1, e.g., for every fatality involving other vehicle user, there was 2 fatal motorcyclists.

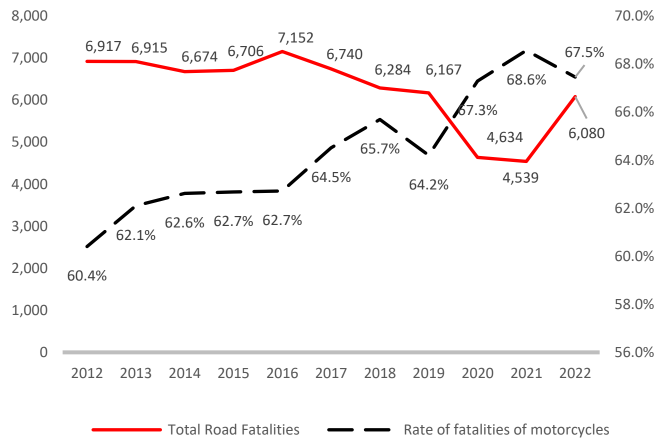

Figure 1: Number of road fatalities and the rate of fatalities based on type of vehicles in Malaysia

To increase the safety of motorcycles in Malaysia, the government has built exclusive motorcycle lanes (EMCL) (see Figure 2) at several locations on federal roads and expressways to segregate them from other vehicles since the late 1980s (Radin Umar and Barton 1997). The first EMCL was constructed along F2 in the early seventies with support from World Bank. It connects the city of Kuala Lumpur and Subang International Airport with a total length of 16 km (Norfaizah et al. 2015). The lane significantly reduced overall crashes by 25%, and 34% of motorcycle crashes, excluding those that occurred on the main carriageway (Radin Umar and Barton 1997). These findings support the notion that segregating motorcycles from other traffic reduces crash exposure and improves the safety of motorcyclists. Based on the recent statistics of road inventory, Malaysia has a total of 262.5 km of motorcycle lane along Federal Road, 36 km in Putrajaya and 98.10 km along tolled highways, which includes both left and right-hand side of the road (PWD 2009, Ishak et al. 2017).

Figure 2: The EMCL (top) and NEMCL (below) for motorcycles

After the success of EMCL, more motorcycle lanes were constructed, thus the Non-exclusive Motorcycle Lane was introduced. The NEMCL is an assigned lane for motorcycles usually positioned on the left-hand side of a road and form as part of the carriageway itself but separated by painted marking to provide separation for motorcyclists with other motorized vehicles. The separation of NEMCL defines the corridor and the right of way that is set aside for motorcycles (see Figure 2). The minimum width of NEMCL is 2.0m and the locations of NEMCL throughout Malaysia. To date, the total length of NEMCL in Malaysia is approximately 199 km and most of NEMCL were located on the single carriageway road. Johor state seems to dominate the list with the longest total length (109 km for both traffic directions) of NEMCL compared to other states. Despite the provision of NEMCL, crashes in-volving motorcycles still occur and have been reported along the road section with NEMCL. It was difficult to identify the location of those motorcycle crashes whether they occurred on the EMCL or on the main carriageway. However, previous research suggests that the presence of NEMCL plays a role in reducing motorcycle crash rates along the road (Alvin Poi et al. 2019) and NEMCL able to reduce motorcycle crash risk by as much as 83% (Alvin Poi 2016, Alvin Poi et al. 2019).

The research in non- exclusive motorcycle lane remains limited, despite there are many studies on motorcycle lane in Malaysia. A study on the utilization of motorcycle lanes was conducted in the year 2016 highlighted that the non-compliance rate of non-exclusive motorcycle lane (NEMCL) varies, as low as 2% to 59%. The same study also evaluated misuse of NEMCL by other road users and the percentage of misuse also varies from 15% to 90% depending on the location of the lane (Ishak et al. 2017). Another study conducted on NEMCL found that the facilities provide the highest benefit when the average daily traffic is about 15,000 per lane and the percentage of the motorcycle is 20% (Wai Hoong 2016). Crash modification factor (CMF) that was developed in the study shows a mixed effect of NEMCL in reducing the number of crashes. However, no statistical model was developed in the project.

Certainly, the crashes involving a motorcycle with other motorized vehicles may still occur with the provision of NEMCL because the motorcycle remains in close contact with other vehicles on the main carriageway (separated by nonphysical barrier only). One of the possible reasons is the usage of NEMCL by other road users. An evaluation of the NEMCL utilization via traffic volume study at two (2) locations in Johor revealed that about 91.5% of motorcyclists are using the provided NEMCL. However, the facilities were also violated by other road users which is 3.9% (851 vehicles) and 1.5% (220 vehicles) of other vehicles are using the NEMCL during peak and off-peak period respectively (Ishak et al. 2017). Other motorized vehicles (e.g. passenger cars and heavy vehicles) are using the NEMCL to overtake other vehicles or for parking (Ishak et al. 2017). From the road safety design view, the end treatment for NEMCL, especially at access and junction, is also a possible contributing factor to crash because observations show that many NEMCL was ceased as an inclusive lane at the crossing area and conflicts may occur with other motorized vehicles. At some NEMCL location, low utilization by motorcyclist was also observed and the possible reason is the inconsistency of NEMCL cross-section layouts such as non-standardized lane width and clear zones, various colors of separator markings and road stud usage along with the separator markings (Abdul Manan and Várhelyi 2012).

The motorcycle facilities in Malaysia make up less than 1% of the whole length of primary roads (Federal Roads) (PWD 2009), despite its reliability. It is also not clear if non-exclusive motorcycle lanes (NEMCL) can mitigate motorcycle crashes on primary roads (federal roads) (Abdul Manan and Várhelyi 2012). Nonetheless, motorcycle fatalities on roads equipped with these non-exclusive motorcycle lanes (NEMCL) increased by 15% from 2006 to 2007 (Abdul Manan and Várhelyi 2012). Motorcycle crashes have also occurred on motorways and primary roads that are equipped with exclusive motorcycle paths (Norfaizah et al. 2015). From 2006 to 2008, crashes in-volving motorcycles steadily increased along a primary road, designated as F2, which has an exclusive motorcycle path alongside (Abdul Manan and Várhelyi 2012, Norfaizah et al. 2015). Thus, the aim of this study is to examines the effectiveness of non-exclusive motorcycle lane (NEMCL) in reducing the probability fatal crash cases in Malaysia, by utilizing more robust and up to date method of probability analysis, i.e., Bayesian Network.

2. Method

2.1. Data

This research utilizes two databases, namely the International Road Assessment Pro-gram (iRAP) and the crash database from the Royal Malaysian Police, focusing along roads with NEMCL. The iRAP database contains a set of road infrastructure details, such as the number of lanes, facilities for motorcycles, speed and other road-related information. The road attributes of the selected primary roads with NEMCL are collected as part of the iRAP Malaysia study in 2015. The iRAP Malaysia study was conducted to assess the risk of crashes on high volume roads throughout the country by inspecting geo-referenced images recorded using a drive-through survey system. Road images for every 100m section were inspected for over 50 road attributes related to the road geometrics, cross sections, roadside design and facilities for vulnerable road users. In the inspection process (or more commonly known as data coding), the relevant categories in the iRAP model for each road attribute were determined for every 100m distance. For example, a 3.5m lane was categorized as 'wide', the presence of street lighting was coded as 'present' etc. On the other hand, police databases contain information about all types of crashes that happen on the road with NEMCL, vehicles involved, the severity of crashes and victims' details. Each dataset has geo-referenced coordinates.

2.2. Bayesian Network

Bayesian network is a graphical probability model with directed acyclic that is based on the Bayes' theorem. In the Bayesian network, a node denotes each variable, and the relationship between a pair of nodes is represented by the edge. This relationship refers to the conditional probability of the event of interest from the given information. For example, let A be the event that the collision type is head-on, and B is the event that the crash severity is fatal; then the conditional probability of B given A is as follows:

$$P(A|B) = \frac{P(A \cap B)}{P(B)} \quad (1)$$

This edge can be directional and does not depend on how the relationship is de-fined. Typically, the variables in the Bayesian network are categorical, as the ones used in this paper. A Bayesian network, B = (G, XV); is composed by a Directed Acyclic Graph (DAG), G = (V, E) in which VV: vertices and EE: edges and a random vector Xv = [Xi]iEV with a probability density factorizes according to the DAG as given by equation (2):

$$P(B|D) = P(G,\theta|D) \ \alpha \ P(G|D) \ P(\theta|G,D) \quad (2)$$

where ϴ: parameters and D: data.

The main tasks of the Bayesian network are to infer unobserved variables, parameter learning and structure learning. This paper focuses on the first and last tasks, which are inferring unobserved variables and identifying the likelihood of a crash to happen, given the current information. From the examination of the structure of dependencies between variables, the outcome could either be specified or structured by the field experts; or machine learning algorithms can be used when no information was provided from the experts. The objective of structure learning is to find the DAG that maximizes P(G|D), whereby it can be rewritten as:

$$P(G|D) \alpha \ P(G)P(D|G) \quad (3)$$
$$\alpha \ P(G) \int P(D|G,\theta) \ P(\theta|G) d\theta \quad (4)$$

In this paper, two machine-learning algorithms are employed: Hill Climb (HC) and Tabu. The Hill Climb algorithm is used for solving optimization problem as can be found in Shehab et al. (2018) and Tsamardinos et al. (2006). Both algorithms are categorized as score-based, for which the Bayesian Information Criterion (BIC) is used as the score. Hobæk Haff et al. (2016) proposed that the algorithm is among the simplest method used and hence, its application have been widely popularized in artificial intelligence and is used to find the goal state starting with the initial node. However, the main disadvantage of this algorithm is that it tends to lag in local optimum point. This weakness is overcome by the next algorithm, Tabu.

The Tabu algorithm has similar functions and characteristics as Hill Climb, but with an added advantage. This algorithm utilizes memory that describes the visited solutions. Dünder et al. (2014) explained that this algorithm will add a short-term memory for the links added between moves. There are two main conditions in this algorithm, which are the relaxing and prohibitive conditions. In relaxing conditions, any move that does not improve the solution is accepted, given that there are no more improving moves available. The essence of this condition is to avoid the search to lag at a strict local minimum. Meanwhile, the purpose of a prohibitive condition is to prevent the search from revisiting any previously visited solutions. See Zamzuri et al. (2019) for further detail on the steps involved in this algorithm.

3. Results

Table 1 shows the data used in this study, and the independent variable that was used for the Bayesian Network analysis is the "Fatal crash cases along roads" category. The breakdown of the categories is as follows: (1) Fatal crash cases on road with NEMCL (FCWNEMCL), (2) Fatal crash cases on road without NEMCL (FCXNEMCL), (3) non-fatal crash cases on road with NEMCL (NFCWNEMCL) and (4) non-fatal crash cases on road without NEMCL (NFCXNEMCL). With this approach, the Bayesian Network analysis will predict the probability of fatal and non-fatal crash cases with or without NECML. Dully note that the fatal crash cases used in this study includes all types of vehicles and not just motorcycles specifically. The reason behind using just the fatality data was because police data for injury are still grossly underreported (Abdul Manan and Várhelyi 2012, Kamaluddin et al. 2019).

Table 1: Description of the data

Category	Description	N
Fatal and non-fatal crash cases (Ftlmcfac)*	FCWNEMC	71
	FCXNEMCL	144
	NFCWNME	291
	NFCXNME	433
Year (Yr)	2013	200
	2014	219
	2015	209
	2016	191
	2017	120
Day type (Dytyp)	Weekdays	619
	Weekends	320
State (Stt)	Johor	438
	Kedah	292
	Perak	92
	Selangor	66
	Terengganu	51
Road Type (Rdtype)	Primary road	900
	State road	39
Land use (LndUs)	Undeveloped	175
	Residential	261
	Commercial	399
	Educational	38
	Industrial	66
Area type (Artyp)	Rural	731
	Urban	208
Property access points (Prptyaccptn)	Commercial Access ≥1	183
	Residential	17
	Residential Access <3	87
	None	652
	School zone	62

Category	Description	N
Road Geometry (Rdgeo)	straight	844
	bend	7
	cross junction	35
	t/y junction	53
Crrgwy type (Crrgwy)	Dual	282
	Single	657
Mainline Speed limit (Spdlmt)	60km/h	500
	70km/h	71
	80km/h	121
	90km/h	247
Median type (Mdntyp)	Safety barrier	42
	Physical median	259
	Centre line	638
Num. of lanes (Nmblns)	Two	585
	Four	324
	Six	30
Lane width (Lnwdth)	Wide (≥ 3.25m)	918
	Medium (≥ 2.75m to < 3.25m)	21
Curvature (Crvtr)	Straight or gently	862
	Moderate to	77
Pav. shoulder (Pvdshldr) **	Medium (≥ 1.0m	136
	Narrow (≥ 0m to < 1.0m)	803
Sidewalk (Sdwlkdrv)	Presence of	62
	None	877
Roadside distance (Rdsddis)	0 to <1m	312
	1 to <5m	598
	5 to <10m	29
Roadside severity (Rdsdsv)	Safety barrier - metal	54
	Safety barrier - concrete	13
	Deep drainage ditch	8

Presence of SZ (Pschlzn)	Not a school zone	877		Cliff	7
Vehicle parking (Vhprk)	Low	844		Tree >=10cm	169
	High presence	95		Non-frangible sign >=10cm	579
Street lighting (Strtlght)	Not present	236		Rigid	19
	Present	703		Semi-rigid	36
				Unprotected	54

Note:
FCWNEMCL: Fatal case on roads with NEMCL, FCXNEMCL: Fatal case on roads without NEMCL, NFCWNMECL: Nonfatal case on roads with NEMCL, NFCXNMECL: Nonfatal case on roads without NEMCL, Crrgwy: Carriageway, SZ: School Zone, Pav: Paved
* The dependent variable

3.1. The Network

By using Tabu and HC algorithms as described in the previous section, the network is constructed as observed in Figure 3. Human intervention is also permissible in the Bayesian network, in which a user can specify any relationship to be included or dis-missed from the network. Based on the relationships in Figure 3, the day of the week has no direct relationship with the other variables.

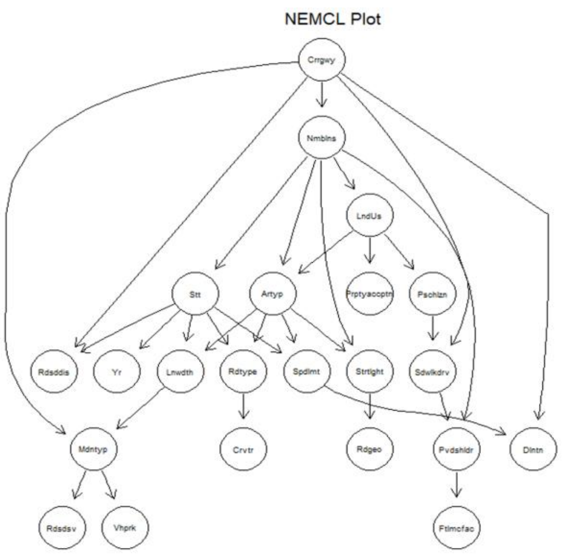

Figure 3: The Bayesian network of NEMCL fatal crash data constructed through HC and Tabu algo-rithms

The suitable causal relationships that were obtained are:
1. Crrgwy → Pvdshldr → Ftlmcfac
2. Crrgwy → Nmblns → Sdwlkdrv → Pvdshldr → Ftlmcfac
3. Crrgwy → Nmblns → LndUs → Pschlzn → Sdwlkdrv → Pvdshldr → Ftlmcfac

The three causal relationships were chosen because they have similar outcomes, i.e., Fatal and non-fatal outcome along NEMCL (Ftlmcfac). Other relationships are discarded as they do not make any sense and are not useful in fulfilling the aim of this study. After thorough analysis and query for probabilities, only 1 relationship are taken into consideration for this study, i.e., relationship 2. This table is generated based on the query done by network prediction based possible and available combination of variables based on the relationship. On the other hand, combination of variables of 'dual carriageway' with '2-lanes' road was taken out of the query as this com-bination are not available in Malaysian roads.

Table 3 is the probabilities of fatal and non-fatal crash cases outcomes based on relationship number 2. Based on Table 3, we can see the fatal and non-fatal outcome of relationship 2 has a higher degree of probability of survivability of all motorist, if the roads is equipped with NEMCL compared to those without. the Bayesian network computed that single or dual carriageway roads with NEMCL, equipped with adequate width of paved shoulder or width of NEMCL lane, i.e., Medium (≥ 1.0m to < 2.4m), have a very low probability of fatal cases ranges from 1.9% to 2.7% outcome. On the other hand, single or dual carriageway roads with narrow NEMCL lane width, i.e., Narrow (≥ 0m to < 1.0m), have a higher probability of fatal cases ranges from 17.2% to 18.8%. Uniquely, for dual carriageway roads with narrow NEMCL width (≥ 0m to < 1.0m), regardless of the number of lanes and with the presence of sidewalk, i.e., typical urban road settings, the probability of fatal crash case to occur is approximately as low as 9.0%. However, this typical urban road settings without NEMCL, the network predicted two times the probability of a fatal crash cases to occur (17.6% to 18.8%). The lowest probability of fatal crash cases to occur, i.e., a low as 1.1%, are along a two lanes single carriageway, with medium width NEMCL but no side-walk configuration, i.e., typical rural road settings. But as the number of lanes in-creases to four-lanes, in this typical rural road setting, the probability of fatal crash cases occurring is more than twenty times the risk, i.e., from 1.5% to 19.0%, if the roads are not equipped with NEMCL. This shows that having NEMCL along rural road settings will benefit all motorists, especially motorcyclists.

Table 3: Probabilities of fatal and non-fatal outcomes based on relationship no. 2 scenario

Crrgwy	Nmblans	Sdwlkdrv	Pvdshldr	Ftlmcfac	Prob.
Dual	Four	With sidewalk	Narrow	FCWNEMCL	9.0%
Dual	Four	With sidewalk	Narrow	FCXNEMCL	18.8%
Dual	Four	With sidewalk	Narrow	NFCWNMECL	32.4%
Dual	Four	With sidewalk	Narrow	NFCXNMECL	40.7%
Dual	Four	None	Narrow	FCWNEMCL	9.3%
Dual	Four	None	Narrow	FCXNEMCL	17.6%
Dual	Four	None	Narrow	NFCWNMECL	29.7%
Dual	Four	None	Narrow	NFCXNMECL	43.0%
Dual	Six	None	Narrow	FCWNEMCL	9.2%
Dual	Six	None	Narrow	FCXNEMCL	17.8%
Dual	Six	None	Narrow	NFCWNMECL	32.6%
Dual	Six	None	Narrow	NFCXNMECL	42.4%
Single	Two	With sidewalk	Medium	FCWNEMCL	1.9%
Single	Two	With sidewalk	Medium	FCXNEMCL	2.7%
Single	Two	With sidewalk	Medium	NFCWNMECL	33.9%
Single	Two	With sidewalk	Medium	NFCXNMECL	60.1%
Single	Two	With sidewalk	Narrow	FCWNEMCL	5.6%
Single	Two	With sidewalk	Narrow	FCXNEMCL	17.2%
Single	Two	With sidewalk	Narrow	NFCWNMECL	32.6%
Single	Two	With sidewalk	Narrow	NFCXNMECL	33.3%
Single	Two	None	Medium	FCWNEMCL	1.1%
Single	Two	None	Medium	FCXNEMCL	1.5%
Single	Two	None	Medium	NFCWNMECL	38.1%
Single	Two	None	Medium	NFCXNMECL	56.7%
Single	Four	None	Narrow	FCWNEMCL	7.9%
Single	Four	None	Narrow	FCXNEMCL	17.8%
Single	Four	None	Narrow	NFCWNMECL	29.7%
Single	Four	None	Narrow	NFCXNMECL	43.0%
Single	Four	With sidewalk	Narrow	FCWNEMCL	11.9%
Single	Four	With sidewalk	Narrow	FCXNEMCL	18.6%
Single	Four	With sidewalk	Narrow	NFCWNMECL	23.9%
Single	Four	With sidewalk	Narrow	NFCXNMECL	40.5%
Single	Four	None	Narrow	FCWNEMCL	7.8%
Single	Four	None	Narrow	FCXNEMCL	19.0%
Single	Four	None	Narrow	NFCWNMECL	31.2%
Single	Four	None	Narrow	NFCXNMECL	44.4%

4. Discussion

This paper examined the application of the Bayesian network in fatal crash cases analysis, specifically in the context of the effectiveness of Malaysia's NEMCL. One of the advantages of the

Bayesian network is its ability to estimate the interrelationships that exist between the variables in the data set (Zamzuri et al. 2019). The information obtained is essential in the causal analysis to determine the following: which event causes the occurrence of a subsequent event; identify the event that occurred first; and which event has the highest chance to occur when given the perceived information. This information is obtained through the Bayesian network that makes this analysis effective, especially in deducing inferences on the unobserved variables.

This network shows that NEMCL is effective in reducing the occurrence of fatal cases down to 0.2% to 1.7% chances or in other words 98.3% - 99.8% survival rate, especially when the road is equipped with paved shoulders next to the NEMCL. This shows that, only sufficient (e.g. (≥ 1.0m to < 2.4m width) NEMCL lane width will save the lives of motorist and this is supported by the findings that indicate that paved shoulder will increase the probability of survivability of motorist, especially motorcyclists, as they usually used paved road shoulder to travel (see Abdul Manan et al. (2017)). In analyzing the typical urban and rural road settings, the network predicted higher probability of fatal crash cases likely hood to occur if urban and rural roads are not equipped with NEMCL (up to 18.4% chance of fatal crash case to occur), and as the number of lanes increases from two lane single carriageway to four-lanes single carriageway for typical rural road setting, the probability of fatal crash cases occurring is more than ten times the risk, if it is not equipped with NEMCL.

This study is not without flaws. The process of merging the two databases is tedious by which each dataset is cleaned up and converted into spatial data and validated through a thorough process. However, due to the inconsistency and inaccuracy of the available data from the police we had to leave out these variables. Moreover, the data collected from the police is not 100% accurate in terms of pinpointing the exact loca-tion of the fatal crashes.

5. Conclusion and Recommendations

It is recommended that more NEMCL be built along Malaysian high-risk roads or with high fatal crash cases or roads with high volume of motorcyclists. Not only that, having a usable paved shoulder next to the NEMCL will increase the probability of survivability of motorist, especially to motorcyclists. If building NEMCL costs too much, having just the paved shoulder also provides a higher chance of survivability for motorist, as shown in this study.

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Quantifying Distance Halo Effects of Fixed Speed Cameras on Malaysian Expressways

Sharifah Allyana[1,] *, Nur Zarifah Harun, Nusayba Megat Johari[1], Muhammad Marizwan Abdul Manan[2]
*Corresponding author: allyana@miros.gov.my

[1]*Road Safety Engineering and Environment Centre, Malaysian Institute of Road Safety Research, 43000 Kajang, Selangor, Malaysia*
[2]*Research Management & Commercialization Unit, Malaysian Institute of Road Safety Research, 43000 Kajang, Selangor, Malaysia*

ABSTRACT

Speeding remains a major road-safety concern on Malaysian expressways, and automated speed enforcement is used to improve compliance with posted speed limits. This study quantified the distance halo effects of fixed speed cameras under the Automated Safety Awareness System (AwAS) at two rural expressway sites, Taiping and Slim River, each with a posted speed limit of 110 km/h. A quasi-experimental before–after design was applied using spot-speed data collected at four measurement points: upstream approach, warning sign, camera location, and 500 m downstream of the camera. Data were collected before implementation, six months after implementation, and at approximately two- and four-year follow-up periods. Speed-limit compliance was assessed using chi-square tests for the pre-implementation and six-month comparison, while lane-specific 85th percentile speeds were examined descriptively at the two-lane Taiping site. Overall compliance increased from 78.1% before implementation to 89.2% after six months, 92.8% after two years, and 94.6% after four years. The most consistent effect occurred at the camera point. At Taiping, camera-point compliance increased from 82.4% to 94.2% after six months and reached 96.3% after four years; at Slim River, it increased from 74.2% to 86.2% after six months ($p = 0.031$) and reached 93.0% after four years. At Taiping, the combined-lane 85th percentile speed at the camera point decreased from 113.6 km/h before implementation to 100.8 km/h after four years, while the fast-lane value decreased from 122.1 km/h to 105.0 km/h. A downstream reduction was observed 500 m after the Taiping camera at six months and two years but was not maintained at four years, particularly for fast-lane traffic. The findings indicate that fixed speed cameras are associated with sustained speed improvements at direct enforcement locations, whereas distance halo effects vary by site, lane, and follow-up period. The results support site-specific and lane-specific monitoring and suggest that corridor-based measures may be required where speed management is needed beyond individual camera sites.

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1. Introduction

Road traffic injuries remain a major global public health concern, with speeding consistently identified as a leading contributing factor to both crash occurrence and severity (World Health Organization, 2018). Higher travel speeds increase the likelihood of collisions and reduce drivers' ability to detect and respond to unexpected hazards, thereby exacerbating crash outcomes and injury severity (Aarts & van Schagen, 2006; Elvik, 2013). Within the Safe System framework, speed management is recognised as a critical pillar because even small reductions in mean speed can yield disproportionately large reductions in serious and fatal crashes (OECD/ITF, 2018).

In Malaysia, speeding is a key contributor to expressway crashes, where higher operating speeds amplify both crash risk and severity. National statistics indicate that around 23% of fatal crashes in 2019 were attributed to speeding and approximately 11% of fatal crashes occurred on expressways. These figures underscore the need for targeted speed management interventions on high-speed road facilities to improve overall network safety performance.

To address speeding behaviour, many countries have implemented automated speed enforcement systems—particularly fixed speed cameras—as a central strategy to improve compliance with posted speed limits. Fixed cameras operate continuously at predefined locations and are often deployed using an overt enforcement approach, where drivers are informed of camera presence through advance warning signage (OECD/ITF, 2018). Meta-analyses and national evaluations have shown that fixed speed cameras can reduce average speeds, lower the proportion of speeding vehicles, and contribute to substantial, long-term reductions in injury crashes; for example, Elvik and Vaa (2004) reported overall crash reductions of around 18–33% on rural roads with fixed cameras, while Gains et al. (2005) found injury crash reductions of 20–33% at camera sites in the United

Kingdom. Similarly, evaluations in North America have demonstrated marked decreases in high-end speeding and associated crash risk following automated enforcement programmes (Chen, Meckle, Wilson, & Cooper, 2000; Retting & Farmer, 2003; Retting, Farmer, & McCartt, 2008).

Beyond the immediate vicinity of enforcement locations, speed cameras can generate broader behavioural changes known as halo effects. Halo effects refer to the persistence of enforcement-induced behavioural changes over time and distance, where drivers continue to comply with speed limits even after passing the enforcement site (Champness, Sheehan, & Folkman, 2005). In this context, distance halo effects describe the spatial extent to which speed compliance and speed profiles are influenced upstream and downstream of the camera location. A recent review of automated speed enforcement halo effects concluded that distance halo is most commonly associated with fixed cameras, whereas time and spillover halo effects are more frequently reported for mobile enforcement (Xu & Wang, 2020). Understanding the magnitude and extent of distance halo effects is therefore essential for optimising enforcement strategies, including camera spacing, sign placement, and integration with other approaches such as mobile and point-to-point (average speed) systems (European Commission, 2018; Elvik, 2013).

Empirical evidence on distance halo effects, however, remains relatively limited and context-specific. Early work by Champness et al. (2005) on an overt mobile speed camera reported substantial reductions in mean and 85th percentile speeds that gradually dissipated with increasing distance from the enforcement vehicle. Gouda and El-Basyouny (2016, 2017) found significant distance halo effects of mobile photo enforcement on urban roads, with violations reduced by 10–17% over distances of approximately 500 m upstream and downstream of the enforcement unit. A European synthesis suggested that typical distance halo effects of fixed cameras can range from a few hundred metres up to several kilometres, depending on enforcement design and context (European Commission, 2018). More recently, studies have also explored halo patterns using high-resolution trajectory data and microsimulation, highlighting that enforcement configuration (fixed versus point-to-point) can substantially influence both speed profiles and crash risk along corridors (D'Andrea et al., 2024; Li et al., 2023). Because enforcement strategy, operational frequency, driver familiarity, and road environment all affect the size and persistence of halo effects, findings from one jurisdiction may not be directly transferable to countries with different traffic and institutional conditions (Xu & Wang, 2020; Elvik, 2013).

In Malaysia, automated speed enforcement was introduced in 2012 under the Automated Enforcement System (AES) and later rebranded as the Automated Safety Awareness System (AwAS) in 2018. The programme adopts an overt enforcement approach supported by three advance warning signs placed approximately 500 m to 2 km before each camera, in accordance with the Traffic Signs (Size, Color, and Type) Rules 1959 (Amendment) 2011. Fixed cameras are installed in permanent housings and connected to a back-office processing system, while mobile cameras are deployed on tripods and operated by enforcement officers. Previous evaluations and operational reports have indicated improvements in speed limit compliance at AwAS camera points; however, there has been limited empirical investigation into how far these effects extend along expressway segments under real-world traffic conditions and over multiple years.

This study aims to address this gap by quantifying the distance halo effects of fixed speed cameras on Malaysian expressways. Using a field-based observational approach, speed data were collected at multiple measurement points representing key stages of driver interaction with enforcement: upstream approach, warning sign zone, camera location, and downstream departure. The analysis incorporates a longitudinal perspective, examining changes in speed limit compliance and 85th percentile speeds before AwAS implementation, six months after implementation, and at subsequent two- and four-year follow-up periods at two rural expressway sites with different lane configurations. Specifically, the study addresses the following research questions: (i) To what extent do fixed speed cameras improve speed limit compliance at and around the camera point? (ii) How far upstream and downstream of the camera can positive distance halo effects be observed? and (iii) Are these effects sustained over the medium to long term following implementation? The findings are expected to contribute to the scientific understanding of enforcement-related behavioural effects and to the practical optimisation of speed enforcement strategies in Malaysia, including the design and deployment of fixed and average speed enforcement systems under the AwAS program.

2. Method

2.1. Study design

This study employed a quasi-experimental before–after design to evaluate the impact of fixed speed camera enforcement on driver speed behaviour and to quantify the spatial extent of distance halo effects along expressway segments. A longitudinal perspective was adopted, with speed data collected at multiple time intervals: before AwAS implementation, six months after implementation, and at extended follow-up periods approximately two and four years post-implementation.

The design focuses on distance-based behavioural changes by assessing speed compliance at several locations relative to each fixed speed camera. This approach enables the identification of both point-based enforcement effects at the camera and residual behavioural changes upstream and downstream that are attributable to distance halo effects.

2.2. Study sites

The study was conducted at two fixed speed camera locations on Malaysian expressways: Slim River and Taiping. Both sites are situated on rural expressway sections with a posted speed limit of 110 km/h and form part of the Automated Safety Awareness System (AwAS). The locations were selected to represent similar enforcement configurations but different cross-sectional layouts, allowing a comparative assessment of driver behaviour under varying traffic and geometric conditions:

Slim River: Three-lane dual carriageway.

Taiping: Two-lane dual carriageway.

At both sites, fixed cameras operate within an overt enforcement framework. Each is supported by a series of advance warning signs positioned approximately 500 m to 2 km upstream of the camera, in accordance with national traffic sign standards. This consistency in enforcement strategy across sites facilitates meaningful comparison of distance halo patterns while maintaining variation in road environment and lane configuration.

2.3. Measurement framework

To quantify distance halo effects, a structured measurement framework was established consisting of four predefined speed measurement points representing key stages of driver interaction with the enforcement system as shown in Table 1.

Table 1: Speed measurement framework and behavioural interpretation relative to the AwAS fixed speed camera

Measurement point	Location description	Behavioural interpretation
Upstream approach	500 m before first AwAS warning sign	Baseline / pre-awareness behaviour
Warning zone	At AwAS warning sign	Awareness-induced adjustment
Enforcement point	At fixed speed camera	Direct enforcement effect
Downstream departure	500 m after camera	Residual (distance halo) effect

This framework captures how driver speed behaviour evolves spatially as vehicles approach the camera, receive warning information, pass the enforcement point, and depart the enforced section.

2.4. Data collection

Speed data were collected using an out-of-road, microwave-based traffic detection device (Smart Sensor) capable of recording individual vehicle speeds without disrupting traffic flow. The device was mounted at each measurement point in a manner that did not interfere with normal driving and was configured in accordance with the manufacturer's guidelines regarding mounting height, alignment, and detection range as shown in Figure 1.

Data collection was conducted during off-peak periods to minimise the influence of congestion and ensure that observed speeds reflected near free-flow conditions. Each measurement session at a given point and time period comprised a continuous one-hour observation. Speed data were obtained at the four measurement points for the following periods at each site:

- Before AwAS enforcement implementation.
- Six months after implementation.
- Approximately two years after implementation.
- Approximately four years after implementation.

Due to operational, equipment, and safety constraints, simultaneous measurement at all four points was not feasible. Instead, data were collected sequentially across the points within each study period. To enhance comparability, efforts were made to maintain similar environmental and traffic conditions across all sessions, including fair weather, dry pavement, and the absence of unusual events such as roadworks, incidents, or local special events. Only valid speed records captured within the defined observation window were included in the analysis.

Figure 1: Smart Sensor microwave-based traffic detector set-up at a fixed speed-camera measurement location.

2.5. Speed indicators

Driver behaviour was evaluated using two primary indicators: speed limit compliance and speed distribution characteristics.

2.5.1 Speed limit compliance

Speed limit compliance was defined as the proportion of vehicles travelling at or below the posted speed limit of 110 km/h at each measurement point. For each location and period, the compliance rate was calculated as

$$\text{Compliance rate} = (\text{Number of vehicles with speed} \leq 110 \text{ km/h} / \text{Total traffic volume}) \times 100\%$$

This indicator provides a direct measure of enforcement effectiveness and forms the basis for assessing distance halo effects across locations and periods.

2.5.2. Speed distribution characteristics

In addition to compliance rate, the 85th percentile speed was used to characterise prevailing speed behaviour under near free-flow conditions. The 85th percentile speed represents the speed at or below which 85% of vehicles travel and is widely employed in traffic engineering practice as a robust descriptor of typical operating speeds on a given facility. Examining changes in the 85th percentile speed across locations and time periods provides insight into broader shifts in speed distribution beyond simple binary compliance.

2.6. Statistical analysis

Statistical analyses were conducted to assess the effectiveness of fixed speed camera enforcement and to detect the presence of distance halo effects. For each site and measurement point, speed limit compliance before and after AwAS implementation was compared using the chi-square test of independence. This test evaluates whether observed differences in compliance proportions between periods are statistically significant.

Analyses were performed separately for each measurement point (upstream approach, warning zone, enforcement point, downstream departure) and for each comparison period (before vs. 6 months after; before vs. 2 years after; before vs. 4 years after). A significance level of $\alpha=0.05$ was adopted as the primary criterion for statistical significance, with p-values between 0.05 and 0.10 interpreted as indicating marginal evidence of an effect.

The combination of compliance analyses and 85th percentile speed profiles across space and time enables the identification of: (i) immediate enforcement effects at the camera location; (ii) upstream behavioural changes associated with the presence of warning signs; and (iii) downstream persistence of lower speeds and higher compliance indicative of distance halo effects

2.5. Limitations

Several methodological limitations should be acknowledged. First, data collection at the four measurement points was not carried out simultaneously, which may introduce temporal variability in traffic conditions that cannot be fully controlled. Second, the study is limited to two expressway sites, which constrains the generalisability of the findings to other road types, environments, and enforcement configurations. Third, the analysis is based on aggregated speed indicators and does not explicitly distinguish between vehicle classes or account for detailed traffic flow parameters such as density or headway distributions.

Despite these limitations, the study provides empirically grounded insights into the spatial effects of fixed speed camera enforcement under real-world operating conditions and offers an evidence base for refining speed enforcement strategies on Malaysian expressways.

3. Results

3.1. Speed limit compliance over time at camera point

Figure 2 shows speed-limit compliance at the fixed-camera locations before AwAS implementation and at the six-month, two-year, and four-year follow-up periods. At both sites, compliance at the camera location increased after AwAS implementation and remained higher than the pre-implementation level throughout the follow-up period.

At Taiping, camera-point compliance increased from 82.4% before implementation to 94.2% after six months. Compliance subsequently increased to 95.6% after two years and 96.3% after four years. The total increase between the pre-implementation and four-year periods was 13.9 percentage points.

At Slim River, compliance at the camera point increased from 74.2% before implementation to 86.2% after six months. Compliance continued to increase to 91.3% after two years and 93.0% after four years, representing an 18.8-percentage-point increase from the pre-implementation period.

Across the four observation periods, camera-point compliance was consistently higher at Taiping than at Slim River. However, Slim River showed the larger absolute improvement from the pre-implementation period to the four-year follow-up.

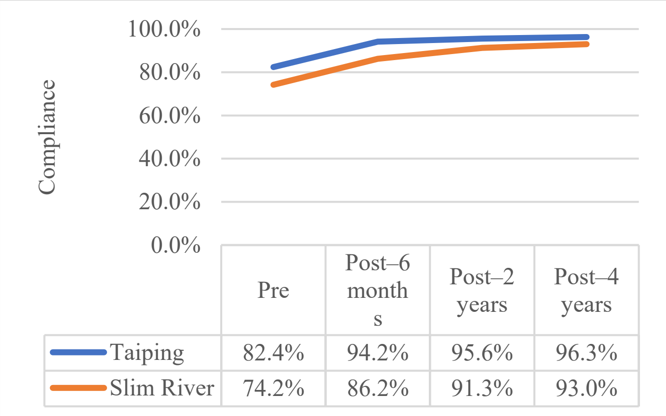

Figure 2: Camera-site compliance over the four observation periods

3.2. Statistical comparison of compliance rates

Table 2 presents speed-limit compliance before AwAS implementation and six months after implementation at the approach, warning-sign, camera, and departure points. Chi-square tests were used to assess whether the observed changes in compliance proportions were statistically significant.

At Taiping, compliance increased at all four measurement points. The largest increases were recorded at the camera point, from 82.4% to 94.2%, and at the departure point, from 81.9% to 93.1%. The differences at the camera point ($\chi^2 = 2.77, p = 0.096$) and departure point ($\chi^2 = 3.64, p = 0.056$) were marginally significant at the 10% level. Changes at the approach point ($\chi^2 = 1.14, p = 0.286$) and warning-sign point ($\chi^2 = 0.09, p = 0.766$) were not statistically significant.

At Slim River, compliance increased at the approach point, camera point, and departure point, but decreased at the warning-sign point. Compliance at the approach point increased from 64.7% to 86.5% ($\chi^2 = 19.16, p < 0.001$), and compliance at the camera point increased from 74.2% to 86.2% ($\chi^2 = 4.64, p = 0.031$). The change at the warning-sign point, where compliance decreased from 80.0% to 65.7%, was also statistically significant ($\chi^2 = 5.57, p = 0.018$). The change at the departure point, from 74.2% to 81.4%, was not statistically significant ($\chi^2 = 1.62, p = 0.203$).

Table 2: Speed limit compliance (%) before and six months after AwAS implementation by site and measurement point

Period	**Approach (%)**	**Warning sign (%)**	**Camera (%)**	**Departure (%)**
Taiping				
Before	77.9	81.4	82.4	81.9
After 6 months	85.7	83.7	94.2	93.1
χ^2	1.14	0.09	2.77	3.64
p-value	0.286	0.766	0.096	0.056
Slim River				
Before	64.7	80.0	74.2	74.2
After 6 months	86.5	65.7	86.2	81.4
χ^2	19.16	5.57	4.64	1.62
p-value	<0.001	0.018	0.031	0.203

Note. Chi-square tests compare the pre-implementation and post–6-month compliance proportions at each measurement point. A significance level of $\alpha = 0.05$ was applied, while $0.05 \le p < 0.10$ was treated as marginally significant.

3.3. Spatial distribution of compliance

Table 3 presents compliance rates at all four measurement points over the pre-implementation, six-month, two-year, and four-year periods.

At Taiping, the camera point recorded the highest compliance rate in all post-implementation periods: 94.2% after six months, 95.6% after two years, and 96.3% after four years. Compliance at the departure point increased from 81.9% before implementation to 93.1% after six months but declined to 86.2% after two years and 72.6% after four years. At the approach point, compliance increased from 77.9% before implementation to 85.7% after six months and 86.9% after two years, before decreasing to 76.0% after four years. Compliance at the warning-sign point increased slightly from 81.4% to 83.7% at six months, then declined to 69.3% after two years and 65.8% after four years.

At Slim River, compliance at the camera point increased progressively across the observation periods, from 74.2% before implementation to 86.2% after six months, 91.3% after two years, and 93.0% after four years. Compliance at the approach point increased from 64.7% before implementation to 86.5% after six months, decreased to 74.6% after two years, and increased to 83.0% after four years. At the departure point, compliance increased from 74.2% before implementation to 81.4% after six months, 77.5% after two years, and 85.7% after four years. The warning-sign point recorded lower compliance after implementation than before implementation, declining from 80.0% before implementation to 65.7% after six months, 52.3% after two years, and 58.6% after four years.

Table 3: Speed limit compliance (%) by measurement point and observation period

	Pre	**Post–6 months**	**Post–2 years**	**Post–4 years**
Taiping				
Approach	77.9	85.7	86.9	76.0
Warning sign	81.4	83.7	69.3	65.8
Camera	82.4	94.2	95.6	96.3
Departure	81.9	93.1	86.2	72.6
Slim River				
Approach	64.7	86.5	74.6	83.0
Warning sign	80.0	65.7	52.3	58.6
Camera	74.2	86.2	91.3	93.0
Departure	74.2	81.4	77.5	85.7

3.4. Lane-specific 85th percentile speeds

Table 4 presents the weekday 85th percentile speeds at Taiping by measurement point and lane during the four observation periods. The posted speed limit at the study site was 110 km/h.

At the approach point, combined-lane 85th percentile speed was 116.9 km/h before implementation, 110.1 km/h after six months, 109.9 km/h after two years, and 116.5 km/h after four years. The fast-lane 85th percentile speed remained above 120 km/h in all periods, ranging from 121.5 km/h to 125.6 km/h. Slow-lane values ranged from 103.0 km/h to 112.1 km/h.

At the warning-sign point, the combined-lane 85th percentile speed was 114.7 km/h before implementation and 112.0 km/h after six months, then increased to 123.2 km/h after two years and 125.0 km/h after four years. The fast lane recorded 85th percentile speeds of 127.2 km/h before implementation, 124.1 km/h after six months, 135.7 km/h after two years, and 137.3 km/h after four years. Slow-lane values were lower but increased from 102.0 km/h before implementation to 113.1 km/h after four years.

At the camera point, combined-lane 85th percentile speed declined from 113.6 km/h before implementation to 102.7 km/h after six months, 102.0 km/h after two years, and 100.8 km/h after four years. The fast-lane 85th percentile speed declined from 122.1 km/h before implementation to 105.0 km/h after four years, while the slow-lane value declined from 104.6 km/h to 96.9 km/h.

At the departure point, combined-lane 85th percentile speed declined from 113.6 km/h before implementation to 104.5 km/h after six months and 101.1 km/h after two years, before increasing to 119.7 km/h after four years. Fast-lane values were 119.8 km/h before implementation, 110.1 km/h after six months, 117.0 km/h after two years, and 125.8 km/h after four years. Slow-lane values remained below 110 km/h in all periods.

Table 4:.Lane-specific 85th percentile speeds (km/h) at measurement points before and after AwAS implementation during weekday periods at Taiping

Lane	Pre	Post–6 months	Post–2 years	Post–4 years	Change: pre to 4 years
Approach					
Slow lane	104.6	103.0	103.7	112.1	+7.5
Fast lane	125.6	121.5	123.8	125.6	0.0
Both lanes	116.9	110.1	109.9	116.5	−0.4
Warning sign					
Slow lane	102.0	104.0	108.8	113.1	+11.1
Fast lane	127.2	124.1	135.7	137.3	+10.1
Both lanes	114.7	112.0	123.2	125.0	+10.3
Camera					
Slow lane	104.6	98.4	95.9	96.9	−7.7
Fast lane	122.1	110.4	109.3	105.0	−17.1
Both lanes	113.6	102.7	102.0	100.8	−12.8
Departure					
Slow lane	105.5	95.7	101.1	103.8	−1.7
Fast lane	119.8	110.1	117.0	125.8	+6.0
Both lanes	113.6	104.5	101.1	119.7	+6.1

4. Discussion

This study evaluated the spatial and longitudinal effects of AwAS fixed speed cameras at two rural Malaysian expressway sites. The results show that the strongest and most persistent improvements occurred at the fixed-camera locations. In contrast, the patterns at approach, warning-sign, and downstream departure points varied by site and follow-up period. The lane-specific analysis at Taiping further showed that combined-lane measures can conceal continued high-end speeding in the fast lane away from the camera point.

These findings contribute evidence on the distance halo effects of fixed cameras in a Malaysian expressway setting. They demonstrate the importance of examining speed behaviour across multiple locations, over time, and, where possible, separately by lane rather than drawing conclusions from camera-site results alone.

4.1. Direct fixed-camera effect

The most consistent finding was the direct effect at the camera location. Compliance increased and remained high at both sites throughout the observation periods. At Taiping, camera-point compliance rose from 82.4% before implementation to 96.3% after four years. At Slim River, it increased from 74.2% to 93.0% over the same period.

The lane-specific weekday results at Taiping reinforce this conclusion. The combined-lane 85th percentile speed at the camera point decreased from 113.6 km/h before implementation to 100.8 km/h after four years. The largest decrease occurred in the fast lane, where the 85th percentile speed declined from 122.1 km/h to 105.0 km/h. The slow-lane value also declined, from 104.6 km/h to 96.9 km/h.

These patterns suggest that fixed-camera enforcement was associated with reduced high-end speed behaviour at the precise enforcement point, including among fast-lane vehicles that displayed the highest pre-implementation operating speeds. Because no inferential tests were conducted for the 85th percentile data, these changes should be interpreted as sustained descriptive patterns rather than statistically verified effects.

The result is consistent with Champness et al. (2005), who reported that an overt mobile speed camera produced the largest speed reduction immediately adjacent to the camera. Their study found a 6 km/h reduction in mean speed, a 7 km/h reduction in 85th percentile speed, and a decline in the proportion of vehicles exceeding the 100 km/h limit from 53% to 16% at the camera site. Although that study examined short-term mobile-camera deployment rather than long-term fixed-camera enforcement, both studies show that camera effects are most pronounced at the enforcement location.

The results are also consistent with systematic evidence that automated speed enforcement can reduce speeds and crash outcomes near camera sites. Pilkington and Kinra (2005) reported reductions across the included studies in collisions, injuries, and deaths following speed-camera installation. Wilson et al. (2010) likewise concluded that speed-camera interventions were consistently associated with reductions in crashes in camera areas. The current study did not assess crashes; nevertheless, its reduction in compliance violations and high-percentile speeds supports the expected behavioural mechanism through which enforcement may improve safety

4.2. Downstream halo effect

The Taiping results indicate a downstream camera-related speed reduction at 500 m after the camera during the initial follow-up periods. Compliance at the departure point increased substantially six months after implementation, and the combined-lane 85th percentile speed fell below the posted limit at both the six-month and two-year observations.

However, the downstream pattern was not stable throughout the full four-year period. Compliance at the Taiping departure point declined from 93.1% after six months to 72.6% after four years, while the combined-lane 85th percentile speed increased to 119.7 km/h. The four-year fast-lane 85th percentile speed reached 125.8 km/h, above both the speed limit and its pre-implementation value. Therefore, the results support a short- to medium-term downstream halo at this 500 m location but do not demonstrate a sustained downstream effect for all traffic over four years.

This pattern corresponds broadly to the distance-halo findings of Champness et al. (2005). They observed that speed reductions began to diminish by 500 m downstream, persisted to approximately 1 km, and had dissipated by 1.5 km downstream. The present study cannot identify the full downstream range because it measured only one departure point, 500 m after the camera. Nonetheless, the initial Taiping reduction at that location is consistent with a localised downstream effect.

Fu and Liu (2023) provide an especially relevant fixed-camera comparison. Based on more than 1.34 million taxi GPS trajectories, they found that fixed automated cameras produced variable upstream and downstream halo distances across sites. Their estimated downstream distances ranged from approximately 10 m to 580 m, while upstream distances ranged from approximately 8 m to 2,180 m. The Taiping departure measurement lies near the upper end of their reported downstream range. The present finding of an early reduction at 500 m, followed by an inconsistent four-year result, supports the view that a fixed camera's influence zone is site-specific and should not be assumed to be permanent or identical across road conditions.

4.3. Upstream effects and warning signs

The upstream findings were more variable than the direct camera-point results. At Taiping, compliance improved at the approach point during the six-month and two-year observations but fell slightly below the pre-implementation level at four years. Compliance at the warning-sign point showed a small increase at six months but subsequently declined, reaching 65.8% at the four-year follow-up. The corresponding lane-specific 85th percentile speeds show that high-end speed behaviour, particularly in the fast lane, remained elevated at upstream locations.

At Slim River, the approach point showed the strongest initial six-month improvement in compliance, increasing from 64.7% to 86.5%, with a statistically significant before–after difference ($p<0.001$). In contrast, compliance at the warning-sign point declined from 80.0% to 65.7%, and this difference was statistically significant ($p=0.018$). The result confirms that statistical significance reflects a measurable change between periods; it must not be interpreted automatically as a positive enforcement outcome.

The contrasting responses at Taiping and Slim River indicate that advance warning signs do not necessarily produce a uniform or sustained upstream behavioural response. Champness et al. (2005) found negligible upstream halo effects for an overt mobile camera, whereas Fu and Liu (2023) reported a wide range of upstream halo distances for fixed cameras. The present results align with the latter conclusion: upstream responses differed by site and period.

Several unmeasured factors may contribute to this variation, including the precise distance and visibility of warning signs, road geometry, lane configuration, traffic composition, traffic volume, and drivers' familiarity with the route. These factors were not measured in the present study, so they should be treated as plausible explanatory factors rather than causal explanations.

4.4. Lane-specific speeding behaviour

The lane-specific 85th percentile analysis provides an important extension to the compliance results. Fast-lane 85th percentile speeds were generally higher than slow-lane speeds at all measurement points. The difference was especially evident at the approach and warning-sign locations, where fast-lane speeds remained well above 110 km/h in every observation period.

At the four-year follow-up, fast-lane 85th percentile speeds were 125.6 km/h at the approach point, 137.3 km/h at the warning-sign point, 105.0 km/h at the camera point, and 125.8 km/h at the departure point. In comparison, the corresponding slow-lane values were 112.1 km/h, 113.1 km/h, 96.9 km/h, and 103.8 km/h. The disparity confirms that combined-lane statistics may mask persistent high-end fast-lane speeding outside the immediate camera zone.

The narrowing of the lane difference at the camera point is notable. Although fast-lane vehicles had substantially higher baseline speeds, the fast-lane 85th percentile value was below the posted speed limit at the two- and four-year follow-ups. This suggests that camera-related speed change extended to both lanes at the direct enforcement location.

This result is relevant to research comparing fixed and point-to-point speed enforcement. Safavi-Naini et al. (2024) used simulation methods to examine driver behaviour under fixed and average-speed camera systems and noted that fixed cameras can be associated with localised speed reductions followed by acceleration beyond the camera site. They concluded that point-to-point enforcement could support more consistent speed control over an extended section than fixed cameras alone. Although their findings come from a microsimulation study rather than observed Malaysian traffic, the Taiping pattern—sustained camera-point reduction alongside elevated fast-lane speeds away from the camera—suggests that longer-distance speed management should be evaluated where corridor-wide compliance is the objective

4.5. Implications for AwAS speed-enforcement planning

The results support fixed cameras as targeted point-based speed-management measures. The continued high camera-point compliance at both sites and the long-term reduction in Taiping's camera-point 85th percentile speeds suggest that AwAS cameras can influence speed choice at locations where speed reduction is most needed.

However, the results do not support treating a single camera as a complete corridor-level solution. The inconsistent upstream effects, the decline in Taiping departure-point compliance over time, and the continued high fast-lane speeds outside the direct camera zone indicate that spatial effects are variable and may weaken over time.

Where the objective is to manage speed across a longer expressway segment, AwAS may consider site-specific combinations of measures: strategically spaced fixed cameras, targeted mobile-camera operations, repeated dynamic speed messages, and point-to-point average-speed enforcement. Fu and Liu (2023) show that camera-related halo ranges vary materially by site, supporting the use of local speed-profile data rather than universal camera-spacing assumptions. Any adoption of corridor-based measures should be tested through structured Malaysian field evaluations before broad implementation.

4.6 Limitation

The findings should be interpreted in light of several limitations. Speed data were collected sequentially rather than simultaneously at the four measurement points, and the study included only two rural expressway sites. In addition, chi-square testing was limited to compliance proportions for the pre-implementation versus six-month comparison, while lane-specific 85th percentile speeds were interpreted descriptively.

Future research should include a larger number of sites, simultaneous multi-point and lane-specific observations, vehicle-level speed data, and matched control sites without cameras. These improvements would allow formal testing of changes in high-percentile speeds, adjustment for traffic and environmental conditions, and more precise estimation of the distances at which camera-related speed effects emerge and dissipate. A denser measurement layout, such as measurements at 500 m intervals upstream and downstream, would also facilitate estimation of the operational halo range of AwAS cameras, as demonstrated by Champness et al. (2005).

5. Conclusion and Recommendations

This study quantified the distance halo effects of AwAS fixed speed cameras at two rural Malaysian expressway sites. The results show that implementation was associated with increased speed-limit compliance at the camera locations and that the most consistent reduction in 85th percentile speed occurred at the direct enforcement point.

At Taiping, the combined-lane 85th percentile speed at the camera point decreased from 113.6 km/h before AwAS implementation to 100.8 km/h at the four-year follow-up. The corresponding fast-lane 85th percentile speed declined from 122.1 km/h to 105.0 km/h. A downstream speed reduction was observed 500 m after the camera at the six-month and two-year observations; however, this pattern was not maintained at the four-year follow-up, particularly for fast-lane traffic.

The findings indicate that fixed cameras can function as effective point-based speed-management measures, but their influence outside the direct enforcement location is variable across sites, lane groups, and follow-up periods. This conclusion is consistent with previous research showing that camera-related speed reductions are generally greatest at or near the enforcement point and that distance halo effects depend on local conditions and enforcement context (Champness et al., 2005; Fu & Liu, 2023).

In view of these findings, AwAS deployment should consider not only the immediate camera location but also the spatial and lane-specific pattern of driver speed behaviour. Although fixed cameras may support substantial and sustained speed reductions at targeted high-risk locations, the mixed upstream and downstream findings indicate that enforcement design should be tailored to local road conditions, traffic characteristics, and the safety objective of each expressway segment. The following recommendations are proposed:

- Retain and prioritise fixed speed cameras at locations with documented excessive speeding and speed-related crash risk. The sustained camera-point speed reductions observed in this study support their role as targeted, point-based speed-management measures.
- Determine camera placement and spacing using site-specific speed profiles. The reduced speeds observed 500 m downstream of the Taiping camera should not be treated as a universal camera-spacing rule because halo effects varied by site, lane, and follow-up period (Fu & Liu, 2023).
- Include lane-specific speed monitoring on multilane expressways. Combined-lane indicators may conceal continuing high-end speeding in the fast lane, as observed at the Taiping approach, warning-sign, and departure points.
- Apply corridor-based enforcement where the objective is to manage speeds over longer road lengths. Strategically spaced fixed cameras, targeted mobile enforcement, or point-to-point average-speed enforcement may be more suitable than reliance on a single fixed camera. Evidence reviews indicate that average-speed enforcement can promote speed compliance across an enforced corridor (Soole et al., 2013).

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