BANGKOK 2024

E-Proceedings
of
The 5th International Conference on Highway Engineering 2024

"Future-Proofing Roads for Asia and Beyond"

4 - 6 September 2024
Bangkok International Trade & Exhibition Centre (BITEC)
Bangkok, Thailand

Organised by
Department of Highways
and
Roads Association of Thailand

Edited by
Ponlathep Lertworawanich, Ph.D.
Auckpath Sawangsuriya, Ph.D.
Harutus Phoban, Ph.D.

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Preface

This E-proceedings contains papers from the **International Conference on Highway Engineering 2024 (iCHE2024)** with the theme of **"Future-Proofing Roads for Asia and Beyond"**, held in Bangkok, Thailand, on September 4-6, 2024. This conference is the 5th International Conference on Highway Engineering in this conference series which serves as the platform for national and global leaders, policy-makers, industry professionals, specialists, research scholars, and academia to attend and exchange knowledge, experience, and insights on roads and road transport in these following topics: (a) efficient, inclusive, and safe road management, (b) smart mobility, digital technology, and innovation for roads, and (c) sustainability and resilience of road networks.

This E-proceedings includes a collection of papers from three main tracks of the iCHE2024. **Track A** involves efficient, inclusive, and safe road management. 37 papers were collected in this track. These papers described a wide range of road administrator tasks from planning for effective road networks to managing road infrastructure and transportation system for promoting economic growth and social development as well as improving the lives of citizens across the country. In addition, they also covered road safety management, which is essential towards achieving social equity in accessibility in rural areas.

Track B is associated with smart mobility, digital technology, and innovation for roads. 12 papers were collected in this track. These papers summarized mobility on roads, which was a crucial aspect of modern society, enabling people to access essential services, to engage in economic activities, and to connect with others. The papers addressed the application of new technologies and digital transformation concept in road transport, which optimized the road network operations and enhance the intelligent transportation system. In addition, they also discussed the implementation of emerging technologies and innovations that could help supporting road agencies during the design, construction, operation, and maintenance of roads.

Track C involves sustainability and resilience of road networks. 16 papers were collected in this track. These papers described sustainable and resilient road infrastructure and networks to ensure the serviceability and reliability of road transportation systems. The papers also demonstrated that an increasingly significant global impact of climate change and natural hazards such as floods, landslides, and earthquakes had a devastating impact on road networks, disrupted transportation, and caused significant economic and social harm. The papers presented the resilience of road networks, the development of robust disaster management plans, the investment in resilient infrastructure to mitigate the impact of these events as well as the ongoing monitoring and adaptation to changing conditions. In addition, they also discussed about the decarbonization efforts e.g. the use of low-carbon materials and the adoption of sustainable construction practices, making transportation systems more resilient to the impacts of climate change, and reducing the carbon footprint of road construction and maintenance.

The Editors,

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Track C

Sustainability and Resilience of Road Networks

Carbon Reduction initiatives by Indonesian Road Administrator: Promoting the utilization of Natural Asphalt

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ABSTRACT

Indonesia announced its ambitious objective to reach net zero emissions by 2060 during the UN Climate Change Conference (COP 26) in 2021. Report by Minister of Environment and Forestry, in September 2022, Indonesia submitted the Enhanced NDC to the UNFCCC Secretariat. The document contains the increased target of emission reduction from 29 percent to 31.89 percent unconditionally and from 41 percent to 43.20 percent conditionally. In conjunction with the objective, Ministry of Public Works and Housing announce Guideline for Sustainable Construction, which state three principles of sustainability: economically viable and support public welfare, preserve environmental preservation, and reduce social disparity. This paper explores the carbon reduction strategies by Indonesia Road Administrator. Four initiatives discussed are (i) Establishing Indonesian Green Road concept, (ii) Utilization of material which has less carbon footprint, (iii) New Technology supporting carbon footprint reduction, (iv) Promoting utilization of Buton Asphalt (Indonesian natural asphalt/Asbuton) instead of petrol-based asphalt. The results demonstrate that utilization of Buton Natural Asphalt face several challenges and need further government intervention to speed up. This work contributes mostly by discussing and offering suggestions for the initiatives. It also provides critics and suggestions for further development.

Keywords: Buton Natural Asphalt, carbon reduction, green road, resilience road

1. INTRODUCTION

Indonesia announced its ambitious goal of achieving net zero emissions by 2060 at the UN Climate Change Conference (COP 26) in 2021. Following this announcement, the country's Ministry of Energy and Mineral Resources (MEMR) and the International Energy Agency (IEA) have been collaborating on detailed scenario and policy analyses to understand the implications for Indonesia's energy sector. Through robust and granular modeling, both institutions have explored pathways to net zero for Indonesia's energy sector, and the key findings of this collaboration are summarized here (International Energy Agency, 2022).

Indonesia's development has been an extraordinary success, largely supported by conventional energy sources. Over the past fifty years, Indonesia has maintained rapid growth, ranking as the fourth-fastest growing large economy in the world after Korea, Singapore, and China. The export of coal and natural gas has significantly contributed to this growth and Indonesia's positive trade balance. By 2021, nearly all households in Indonesia had access to electricity, and the percentage of the population below the national poverty line decreased from 60% in 1970 to less than 10% today. Indonesia is the world's fourth-most populous country, seventh-largest economy, twelfth-largest energy consumer, and the largest coal exporter.

In conjunction with the objective of achieving net zero emissions by 2060, the Ministry of Public Works and Housing has announced a comprehensive Guideline for Sustainable Construction. This guideline lays out a strategic framework to ensure that future construction projects in Indonesia align with the broader goals of sustainability and environmental stewardship. The guideline is built on three core principles of sustainability: economic viability and support for public welfare, environmental preservation, and the reduction of social disparity. Firstly, the principle of economic viability and support for public welfare emphasizes the need for construction projects to be financially sustainable while also contributing positively to the community. This involves ensuring that projects are cost-effective, provide long-term economic benefits, and create jobs and opportunities for local populations. By focusing on economic viability, the guideline aims to foster growth and development that can sustain the population and improve overall quality of life. Secondly, the principle of environmental preservation highlights the importance of protecting and maintaining natural resources and ecosystems. This includes using environmentally friendly materials, implementing energy-efficient technologies, and reducing waste and emissions associated with construction activities. The guideline advocates for practices that minimize the environmental footprint of construction projects, thereby contributing to the broader goal of reducing carbon emissions and combating climate change. Lastly, the principle of reducing social disparity addresses the need to ensure that the benefits of construction and development are distributed equitably across all segments of society. This principle focuses on creating inclusive projects that provide equal access to resources and opportunities, particularly for marginalized and disadvantaged communities. By reducing social disparity, the guideline seeks to promote social cohesion and ensure that all citizens can benefit from the country's development.

This paper explores the carbon reduction strategies by Indonesia Road Administrator. Four initiatives discussed are: (i) Establishing Indonesian Green Road concept, (ii) Utilization of material which has less carbon footprint, (iii) New Technology supporting carbon footprint reduction, (iv) Promoting utilization of Buton Asphalt (Indonesian natural asphalt/Buton Natural Asphalt) instead of petrol-based asphalt.

This paper is structured as an analytical report, describing the initiative and provide critique to the initiatives instead of research paper with structured hypotheses. Thus, the heading of the paper is mainly the main topic of the initiatives.

2. INDONESIAN GREEN ROAD CONCEPT

The first initiative is establishing the Indonesian Green Road Concept and strategies to achieve the vision. The Indonesian Green Road Concept aims to promote sustainable and environmentally friendly road construction and maintenance practices. Key aspects include using low carbon materials, such as recycled materials and natural asphalt like Buton Asphalt, and implementing energy-efficient technologies. The concept emphasizes designing roads to minimize environmental impact, incorporating energy-efficient construction methods, and utilizing renewable energy sources for road infrastructure (Djalante et al., 2020; Umer et al., 2016).

Additionally, the concept focuses on environmental preservation and the reduction of social disparity. It involves measures to protect local ecosystems, manage natural resources responsibly, and ensure equitable distribution of benefits from sustainable road projects. The Indonesian Green Road Concept is part of the government's broader effort to align with global sustainability standards, reduce carbon emissions, and support economic development through cost-effective, eco-friendly infrastructure.

The Indonesian Green Road concept encourages the implementation of environmentally friendly technologies and monitors their application within the Directorate General of Highways. The technologies are: Plastic Asphalt, CPHMA (Cold Pave Hot Mix Asbuton), Rubber Asphalt, Zeolite, Slurry and quick patch for preventive maintenance, Cold Mix Recycling Foam Bitumen (CMRFB), Reclaimed Asphalt, usage of Fly Ash, usage of Tailing, local material, Cement Treated Base, Steel Slag, Slope Protection Technologies, and Foam Mortar.

3. LESS CARBON FOOTPRINT MATERIAL AND TECHNOLOGY

The second and third initiative is utilization of less carbon footprint material and new technology. Those material is categorized as: (a) warm mix asphalt, (b) cold mix, (c) recycled asphalt, (d) rubberize asphalt, (e) plastic as a filler, (f) utilizing coal waste such as fly ash and bottom ash (FABA) as asphalt filler, (g) utilization of tailing, (h) usage of local material.

Warm Mix Asphalt (WMA) is less carbon footprint than Hot Mixed Asphalt. This technique is a mixed technique asphalt mixed and compacted with a temperature of around 30°C lower than hot mix asphalt, but with quality equivalent to hot asphalt mix, and nature environmentally friendly. By lowering the mixing temperature, the energy used for mixing is less. The low production temperature of Warm Mix Asphalt (WMA) offers such advantages. First, it can greatly lessen environmental impacts, such as global warming and the emission of gases and fumes. Second, it provides an economic benefit by directly reducing energy consumption (Milad et al., 2022).

Cold mix asphalt consists of a blend of emulsified or cutback asphalts, aggregate, and water. It does not need heating and can be applied directly to the surface from the bag without requiring heavy equipment. This type of asphalt is suitable for cold patch repair projects. Cold mixtures are produced without heating the aggregate, enabled by a specific emulsion that breaks either during mixing or compaction. Once the emulsion breaks, it coats the aggregate and gradually increases its strength. These mixtures are especially suitable for light traffic roads. Their low-temperature production results in significant energy savings and reduced emissions (Thives & Ghisi, 2017).

Recycled Asphalt, also known as Reclaimed Asphalt Pavement (RAP), is material reclaimed from existing asphalt pavement, which is then processed and reused in new asphalt mixtures. This process involves milling the old asphalt, crushing and screening it, and mixing it with new asphalt binder and aggregate to create fresh asphalt for paving. Recycled asphalt is environmentally friendly because it reduces waste and conserves natural resources. By reusing existing materials, the need for disposal in landfills is minimized, and the demand for new raw materials like aggregates and asphalt binders is lowered. This process also consumes less energy than producing new asphalt, leading to lower greenhouse gas emissions and reduced release of volatile organic compounds (VOCs). Additionally, the cost-effectiveness of recycled asphalt supports sustainable pavement management by providing durable, high-quality pavement while promoting environmental responsibility (Yaro et al., 2023).

Rubberized asphalt concrete is a road paving material made by blending ground-up recycled tires with asphalt to produce a binder which is then mixed with conventional aggregate materials. Using scrap tires and adding them into asphalt mix could save CO2 emission and energy (Riekstins et al., 2022).

Incorporating plastic waste into asphalt mix offers several environmental advantages. Firstly, it significantly diminishes the volume of plastic waste destined for landfills or oceans, thereby alleviating the burden of plastic pollution on the environment. This practice transforms plastic waste into a valuable resource, reducing the need for new asphalt binders derived from petroleum and thereby conserving natural resources. Additionally, the process typically requires less energy compared to traditional asphalt production methods, resulting in decreased energy consumption and greenhouse gas emissions during manufacturing (Ma et al., 2021). Moreover, the utilization of plastic waste in asphalt enhances the durability and longevity of pavement, leading to reduced maintenance needs and fewer road construction activities over time. This durability improvement not only prolongs the lifespan of roads but also minimizes the environmental impact associated with frequent maintenance and repair activities. Furthermore, the inclusion of plastic waste in asphalt contributes to improved pavement performance, such as increased resistance to deformation and cracking. This leads to smoother roads, which can enhance vehicle fuel efficiency and further reduce emissions. Overall, integrating plastic waste into asphalt mix represents a sustainable solution that addresses waste management challenges, conserves resources, reduces energy use and emissions, and enhances the performance of road infrastructure.

Utilizing fly ash and bottom ash in asphalt mix presents several environmental advantages. Firstly, it reduces the necessity of disposing of these coal combustion by-products in landfills, thus minimizing the environmental repercussions of coal ash disposal. Instead of being discarded as waste, fly ash and bottom ash are integrated into asphalt mixtures, offering a valuable and ecologically sound application for these materials (Azka et al., 2023). Incorporating fly ash and bottom ash into asphalt mixtures aids in conserving natural resources by diminishing the need for raw aggregates and petroleum-derived asphalt binders. By substituting these materials with coal combustion by-products, the depletion of natural resources, such as aggregates and petroleum-based asphalt binders, is alleviated, fostering a more sustainable approach to road construction. Additionally, the utilization of fly ash and bottom ash in asphalt mixtures can improve the engineering properties of the pavement, such as enhanced durability and resistance to rutting and cracking. This results in roads with extended lifespans and reduced maintenance requirements, consequently reducing the environmental impact associated with frequent road repairs and reconstructions. Moreover, integrating fly ash and bottom ash into asphalt mixtures can contribute to energy savings and the reduction of greenhouse gas emissions.

Iron tailings, a solid waste product from iron mining beneficiation processes, have attracted considerable attention in the scientific community due to their potential for effective utilization in asphalt mixtures. While asphalt mixtures with iron tailings coarse aggregates exhibit satisfactory high-temperature performance, their low-temperature performance and moisture stability are relatively poor. However, incorporating limestone as fine aggregate or using modified asphalt with superior properties can address these shortcomings, ensuring that key performance indicators meet technical requirements for pavement application. Furthermore, enhancing the pavement performance of asphalt mixtures containing iron tailings can be achieved through additives like hydrated lime or silane coupling agents, surpassing the performance of conventional modified asphalt mixtures currently used in pavement projects. Therefore, recycling iron tailings in asphalt pavement offers significant benefits in terms of economy, environment, and society.

Table 1 Less Carbon Footprint Technology and Materials

Technology	Added Material
Warm Mix Asphalt	Rubber
Cold Mix Asphalt	Plastic
Recycled Asphalt	Coal waste (fly ash bottom ash)
	Tailing

This session explain technology in asphalt mixture and using added material into asphalt mixture to achieve less carbon footprint asphalt. Generally, the carbon footprint saving is generated by reducing the energy to mix. The additive materials also contributing for saving the carbon footprint by reducing the amount of raw bitumen as well as reducing the byproduct of waste material.

4. UTILIZATION OF NATURAL ASPHALT

This section discusses the utilization of Buton Natural Asphalt.

Asphalt Buton has been utilized in Indonesia through various technologies, yielding different levels of success. Unlike the more commonly known petroleum-based asphalt, Buton asphalt, or Buton Natural Asphalt, is naturally occurring and requires less processing for production and application. This natural asphalt's unique properties and abundant availability make it a valuable resource for sustainable infrastructure development in Indonesia. The reduced need for processing not only lowers production costs but also contributes to environmental conservation by minimizing energy consumption and emissions associated with asphalt production.

4.1 What is Buton Natural Rock Asphalt (Asbuton)?

Buton Natural Asphalt, commonly referred to as Asbuton, is a unique and environmentally friendly alternative to traditional petroleum-based asphalt. Found in the deposits on Buton Island in Southeast Sulawesi, Indonesia, this natural asphalt boasts significant advantages in terms of sustainability and local resource utilization. Asbuton, a natural asphalt derived from the mountains and rocks of Buton Island in Indonesia, boasts a significant deposit of 677.247 million tons with an estimated bitumen content ranging from 15% to 35%, equivalent to approximately 170 million tons of asphalt. Discovered on Buton Island in Southeast Sulawesi since 1924.

Figure 1 Location of Buton Island

Test	Unit	Pen 60/70 Specification	Pen 60/70		Asbuton	
			Test result	Stdev	Test result	Stdev
Penetration, 25 °C, 100 g, 5 s	0,1 mm	60–70	65	2.359	40	2.173
Kinematic Viscosity 135 °C	cSt	≥300	424.01	1.542	528.65	1.542
Softening Point	°C	≥48	51	0.289	58.5	0.503
Ductility, 25 °C, 5 cm/min	cm	≥100	>100	–	>100	–
Flash point with Clevelen Open Cup	°C	≥232	340	0.577	225	1.155
Solubility in Trichloroethylene	%	≥99	99.868	0.089	99.110	0.038
Specific gravity	–	≥1	1.024	0.005	1.05	0.002
Mass Loss	% weight	≤0,8	0.149	0.003	2.3	0.014
Penetration RTFO	0,1 mm	≥54	58.80	1.414	34	0.918
Softening Point RTFO	°C	–	56	0.115	65	0.071
Ductility RTFO	cm	≥100	>100	1.414	90	0.354

Figure 2 Buton Natural Asphalt picture and specification

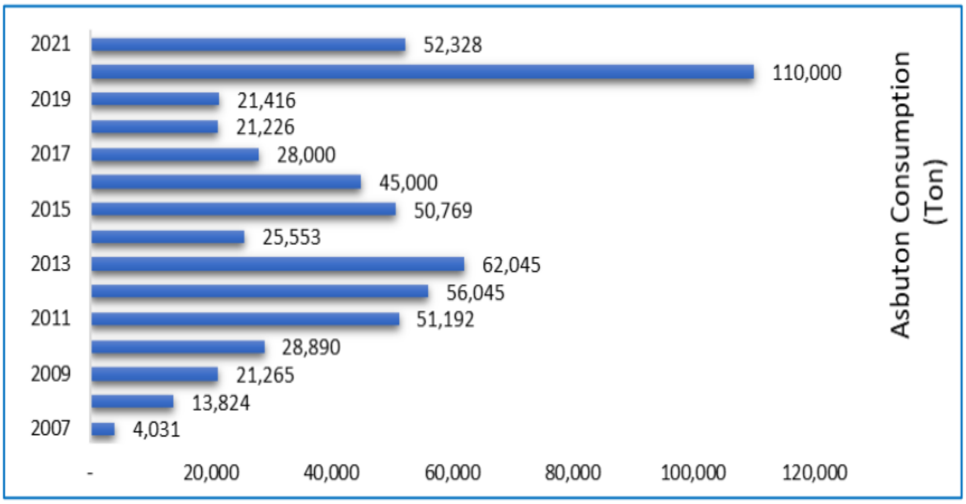
The specification of Buton Natural Rock Asphalt is quite similar with petroleum-based asphalt. Buton Natural Asphalt is a naturally occurring substance with a bitumen content ranging from 15% to 35%, blended with mineral aggregates. This contrasts sharply with petroleum asphalt, which is a refined byproduct of crude oil. The natural composition of Asbuton means it requires significantly less processing compared to petroleum asphalt, making it a more sustainable option with a lower environmental footprint. One of the key benefits of Buton Natural Asphalt is its minimal processing requirements. Since it is naturally mixed with mineral aggregates, the production process is simpler and less energy-intensive. This leads to a reduction in greenhouse gas emissions and energy consumption. On the other hand, petroleum asphalt undergoes extensive refining processes, including distillation and various treatments, which significantly increase its environmental impact.

In terms of physical properties, Buton Natural Asphalt has some distinct characteristics. It generally exhibits good performance at high temperatures, making it suitable for regions with hot climates. However, due to its natural composition, it might require specific additives to enhance adhesion and improve its performance in low-temperature conditions and moisture stability. Petroleum asphalt, being a refined product, has well-understood and engineered properties that make it versatile and reliable for a wide range of applications, including road construction and industrial uses. Buton Natural Asphalt is versatile and can be used in various infrastructure projects, particularly in road construction. Its utilization not only leverages local resources but also supports local economies by reducing dependency on imported materials. In Indonesia, Asbuton has been successfully used in numerous projects, demonstrating its potential as a sustainable construction material. Petroleum asphalt, however, remains the standard choice globally due to its consistency, availability, and extensive research backing its performance in diverse conditions.

From a sustainability perspective, Buton Natural Asphalt stands out. Its reduced processing needs translate into lower carbon emissions and a smaller environmental footprint. Utilizing Asbuton also aligns with efforts to promote sustainable local development, as it taps into a readily available natural resource. Conversely, the production of petroleum asphalt is energy-intensive and contributes significantly to greenhouse gas emissions, highlighting the environmental costs associated with conventional asphalt production.

4.2 Asbuton Consumption

The national demand for asphalt is approximately 1.2 million tons per year. Pertamina (State Owned Company in Oil Industry) fulfills around 272,040 tons (22.27%) of this demand with its oil asphalt production, valued at US$283.77 million. Indonesian natural asphalt, known as Asbuton, from Buton contributes around 21,226 tons (1.74%), worth US$9.13 million. The shortfall is met through imports, totaling 945,180 tons (77.39%) and valued at US$473.77 million. Asbuton resources are vast, with estimated reserves of approximately 792.5 million tons and a reserve capacity of about 182.65 million tons. There are 16 Asbuton processing factories with a total production capacity of around 2.03 million tons per year. However, their current production is only 43,128 tons per year, representing just 2.1% of the total production capacity (Miswanto et al., 2023).



Source: Modified from ASPABI (2019)

Figure 3 Asbuton Consumption 2007-2021

The consumption of Buton Natural Asphalt (Asbuton) during the period from 2007 to 2013 exhibited significant growth, with an impressive average annual growth rate of 32.35%. This remarkable increase can be attributed to the robust support and high commitment from the Ministry of Public Works and Housing, which has been instrumental in promoting and encouraging the use of Asbuton material in various infrastructure projects.

However, this positive trend did not continue beyond 2013. Between 2013 and 2017, the consumption of Asbuton saw a substantial decline, plummeting from 62,045 tons in 2013 to a mere 28,000 tons by 2017, marking a significant decrease of 9.28%. Over the broader period from 2007 to 2018, the total consumption of Asbuton amounted to only 407,840 tons. This figure represents a mere 0.06% of the total deposit reserves available, indicating a vast untapped potential for this natural resource. Interestingly, in 2020, the consumption of Asbuton increased to 110,000 tons. It is because in 2020 the government launches the PEN (Pemulihan Ekonomi Nasional) programs or The National Economic Recovery Program (PEN). PEN is the government's effort so that the national (and regional) economy can quickly recover from the recession that occurred due to the impact of the Covid-19 pandemic. PEN's policy strategy is to save health and the national economy, and one of the programs is buying around 100,000 ton of CPHMA Asbuton to recover the industry. Despite the early growth, the later decline suggests the need for renewed efforts and strategies to fully harness the benefits of Asbuton for sustainable infrastructure development.

4.3 Asbuton Products

In the market, there are 6 types of Asbuton products. These are Asbuton B 5/20, Asbuton B 50/30, Premixed Asbuton, High Bitumen Content Asbuton, Pure Asbuton, and CPHMA (Cold Paving Hot Mix Asbuton).

Asbuton B 50/30 is a type of natural asphalt from the Lawele mine, processed and granulated into granules with specific properties. This asphalt variety has a penetration value of around 50 and a bitumen content of approximately 30%, which means it still contains other minerals. Asbuton B 50/30 is used as a substitute for Penetration Asphalt 60/70 and is processed at the Asphalt Mixing Plant (AMP) with the addition of Penetration Asphalt 60/70 to produce a hot mix equivalent to using Penetration Asphalt 60/70. Besides its use in hot mix production, Asbuton B 50/30 is also utilized for various other types of construction, including Seal Coat, Penetrating Macadam Asbuton Layer (LPMA), or Hot Cold Mixture (CPHMA).

4.4 Discussion

Generally, there are 3 arguments explains that Asbuton is less carbon footprint compared to general petroleum-based asphalt. First, energy used to extract Asbuton from raw material is less compared to energy used to refine asphalt from raw petroleum. Second, Asbuton can be used in Warm Mix and Cold Mix Asphalt which is less energy needed tip process compared to Hot Mix Asphalt. Third, since Asbuton is considered as local product, the transport cost (and energy) of the material is less than product exported from abroad.

Asbuton presents a notable advantage in its extraction process. Unlike the energy-intensive refining of raw petroleum into asphalt, the extraction of Asbuton from its raw material requires significantly less energy. This efficiency stems from the inherent properties of Asbuton and the streamlined extraction techniques employed, leading to reduced environmental impact and lower carbon emissions associated with the initial stages of material acquisition. This table highlights the key differences between the production methods of Buton Natural Asphalt and petroleum-based asphalt.

Table 2 BNA compared to Petroleum-based Asphalt

Aspect	Buton Natural Asphalt	Petroleum-Based Asphalt
Source	Natural deposits on Buton Island, Indonesia	Byproduct of crude oil refining
Extraction Process	Mining (drilling, hauling)	Drilling and pumping crude oil
Processing	Crushing, screening, minimal processing	Distillation, vacuum distillation, solvent de-asphalting, air blowing
Energy Consumption	Low	High
Mixing Temperature	Warm mix, cold mix (lower temperatures)	Hot mix (160-180°C, high temperatures)
Production Complexity	Simple	Complex
Environmental Impact	Lower greenhouse gas emissions	Higher greenhouse gas emissions
Local Availability	Locally sourced, reducing transportation emissions	Often imported, increasing transportation emissions

Asbuton's versatility extends to its application in various asphalt mixes, particularly Warm Mix and Cold Mix Asphalt. These alternative asphalt formulations require substantially less energy during the manufacturing process compared to traditional Hot Mix Asphalt. By integrating Asbuton into these mixes, the overall energy consumption is notably reduced, contributing to a more sustainable paving solution with a diminished carbon footprint.

A significant aspect of Asbuton's environmental benefit lies in its status as a local product. Unlike petroleum-based asphalt, which often involves extensive transportation networks for importation, Asbuton is sourced locally in many regions. Consequently, the transportation distance and associated energy expenditure are significantly reduced. By minimizing the need for long-distance transportation, Asbuton further diminishes its carbon footprint, making it a more environmentally friendly choice for pavement construction.

In essence, these three arguments underscore the superior environmental credentials of Asbuton compared to traditional petroleum-based asphalt, highlighting its efficiency in extraction, versatility in asphalt production, and the localized nature of its sourcing, all contributing to a reduced carbon footprint in pavement construction projects.

5. CONCLUSION

Indonesia's commitment to achieving net zero emissions by 2060, announced at the UN Climate Change Conference (COP 26), necessitates transformative changes in its energy and infrastructure sectors. Collaborations between Indonesia's Ministry of Energy and Mineral Resources (MEMR) and the International Energy Agency (IEA) have provided detailed pathways and policy analyses to support this goal. A key initiative is the Guideline for Sustainable Construction, which emphasizes economic viability, environmental preservation, and social equity, aiming to develop cost-effective, eco-friendly, and inclusive infrastructure projects.

The Indonesian Green Road Concept is central to reducing carbon emissions in the infrastructure sector. This initiative promotes the use of low-carbon materials and energy-efficient technologies, such as Plastic Asphalt, Cold Pave Hot Mix Asbuton (CPHMA), and Rubber Asphalt. These technologies help reduce the environmental impact of road construction while supporting economic growth. Additionally, using Warm Mix Asphalt (WMA), Cold Mix Asphalt, and recycled materials like fly ash and plastic can significantly lower energy consumption and greenhouse gas emissions.

Buton Natural Asphalt (Asbuton) offers a promising sustainable alternative to petroleum-based asphalt. Asbuton requires less processing, reducing energy consumption and emissions, and its local availability minimizes transportation costs and energy use. Utilizing Asbuton aligns with Indonesia's goals of sustainable local development and a reduced carbon footprint, supporting the country's broader efforts to achieve net zero emissions by 2060.

This paper offers the carbon reduction initiative and endorse the use of Natural Asphalt compared to petroleum-based asphalt. However, this paper has limitation such as: the properties of both kind of asphalt is not comprehensively discussed. The lack discussion about method of carbon footprint calculation is also limitation of this paper. Further study is expected could discuss the comparison of both asphalt in more comprehensive and technical manner.

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Lessons Learned from an Application of Geotextile Reinforcement with In-Plane Enhanced Drainage for Pavement Resiliency in Thailand

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ABSTRACT

A number of existing highways in Thailand is encountering various stressors e.g. overloaded vehicles, heavy traffic, extreme weather events, natural hazards etc. To address the importance of resilient pavement, a recently completed road rehabilitation project using enhanced performance offered by the inclusion of geotextile reinforcement was presented herein. The highway was originally completed in 1997 and subsequently rehabilitated periodically since 2015. The roadway was seasonally impacted by flooding and considerable heavy traffic, which resulted in various pavement distresses including longitudinal cracks, block cracks, alligator cracks, and rutting. Several routine and periodic maintenance strategies e.g. deep patching, pavement overlay etc. have been applied but the problem was still reoccurring. These suggested that a traditional method was not applicable for the existing condition. This paper demonstrated an experimental section incorporating the geotextile reinforcement with in-plane enhanced drainage (IPED) showed no abrupt change in moisture and small layer movement during the rainfall event. According to evidence obtained through field observations and field monitoring data of post-construction performance, the proposed experimental section provided valuable insight into the benefits of using IPED geotextile reinforcement in this specific application. Cautions must be exercised in the pavement thickness design and the installation procedure when IPED geotextile is to be used in the road pavement application as well as to assure its hydraulic performance for pavement resiliency.

Keywords: Pavement, Geotextile, Resilience, Performance, Rehabilitation.

1. INTRODUCTION

Extreme weather events e.g. sea level rise, floods, hurricanes, typhoons, extreme heat, and heavy rainfalls and their impacts on the performance of infrastructures are global issues and concerns. A comprehensive knowledge of the basic concepts of infrastructure resilience and recent advances related to climate-resilient infrastructures are therefore necessary for government agencies. Advances in infrastructure resilience evaluation with respect to the design and construction of engineering infrastructures shall be implemented in the management and operational levels. Understanding resilient design, adaptation strategies, evaluation methods, accessing the vulnerability of infrastructures, and monitoring performance parameters are the key success factors for climate-resilient-sustainable infrastructures.

One of the major impacts of climate change on road infrastructures was associated with an increase in the frequency of heavy precipitation events, which resulted in a large amount of water entering roadways within a short period and for most roadways, water remained in the pavement system for a certain period. Several detrimental effects of water on roadway systems were reported for instance: (1) premature pavement failure due to moisture-induced distress, (2) asphalt stripping, (3) reducing stiffness and strength of granular bases and subgrades, (4) surface deformation, (5) cracking in asphalt and concrete pavements, (6) inducing other pavement distresses etc. Haynes and Yoder (1963) found the resilient modulus of gravel decreased by 50% as the degree of saturation increased from 70 to 97%. Jerkins and Kerr (1998) indicated that the subgrade CBRs decreased with the increase in moisture content and eventually approached asymptotes of CBR values between 1 and 2 upon saturation. The rate of decreasing in CBRs also depended on the amount of fines. Since most granular bases contained fine contents, they were sensitive to moisture. Lin et al. (2016) showed that the resilient modulus of aggregate base course decreased dramatically with a little increase in moisture content.

Geosynthetics have been used to improve the performance of roadway systems by incorporating separation, filtration, stiffening, reinforcement, and drainage functions. The use of geosynthetics reinforcements for roadway systems includes minimizing reflective cracking in asphalt overlays, improving the performance of base aggregate layers, providing internal drainage for roadway systems etc. (Correia & Zornberg, 2016; Giroud & Han, 2020). Conventional geosynthetic drains have been commonly used in roadways to manage flow under saturated soil conditions only. However, soil saturation does not usually exist in roadways to enable gravity drainage of water, most pavement systems are typically in unsaturated conditions. A recently developed geotextile reinforcement with in-plane enhanced drainage (IPED) has been introduced to the market and that can allow drainage and remove water under unsaturated conditions. This paper highlights the application of IPED geotextile reinforcement in a recently completed road rehabilitation project in Thailand. The proposed experimental section offers valuable insight into the benefits of using IPED geotextile reinforcement in this specific application including: (1) enhanced lateral drainage of moisture migrating upward from a high groundwater level, (2) enhanced lateral drainage of moisture infiltrating downward from the surface, (3) enhanced layer stiffness and structural integrity, and (4) enhanced separation function between new improved layer and existing or underlying problematic layer.

2. IN-PLANE ENHANCED DRAINAGE (IPED) GEOTEXTILE

Conventional geosynthetic drainage products can only transmit flow once the surrounding soil becomes saturated. This is because of the development of capillary barriers at the interface between materials with contrasting hydraulic conductivity (e.g. a fine-grained soil and a conventional geotextile). A capillary barrier will develop if the soil in contact with a conventional geotextile is unsaturated (Zornberg et al., 2010). A capillary barrier develops when an unsaturated fine-grained soil or finer layer (e.g. silt, clay etc.) is underlain by another unsaturated coarse-grained soil or coarser layer (e.g. sand, gravel etc.) or a porous geosynthetic (e.g. a nonwoven geotextile) (Zornberg et al., 2017). The capillary barrier works based on the contrast between the unsaturated hydraulic properties of the finer and coarser layers. The coarser layer is typically at very low degree of saturation and hence the corresponding unsaturated hydraulic conductivity, which decrease many orders of magnitude with decreasing degree of saturation. Since the unsaturated hydraulic conductivity of the coarser layer is typically very low and can be many orders of magnitude lower than that of the finer layer, the coarser layer acts as an almost impermeable barrier. This is in contrast to what would happen under fully saturated condition when the hydraulic conductivity of the coarser layer would be much higher than that of the finer layer. Figure 1 illustrates the mechanism of capillary barrier which describes the interaction between materials with contrasting hydraulic conductivity (e.g. sand and low plasticity clay) under unsaturated conditions.

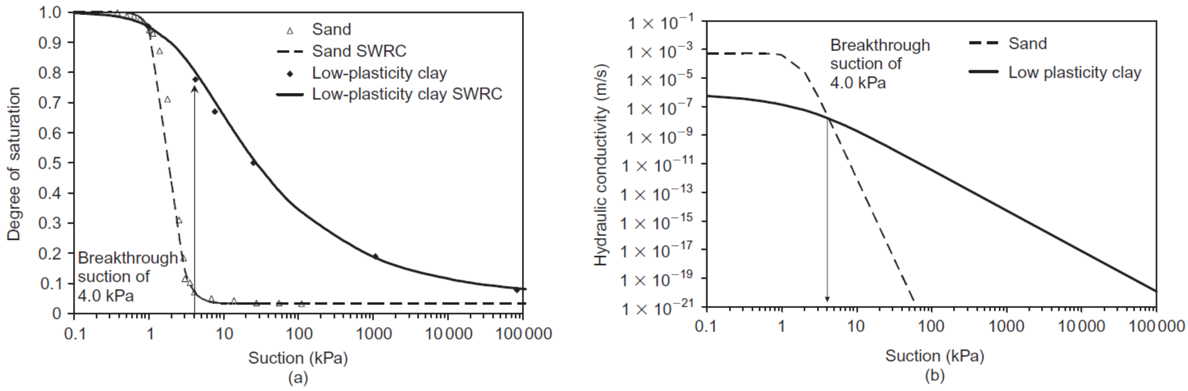


Figure 1 Soil-water characteristic curve and soil hydraulic conductivity curve for a sand (coarser material) and a low-plasticity clay (finer material).
(Zornberg & McCartney, 2007)

An in-plane enhanced drainage (IPED) geotextile manufactured by Solmax (Figure 2) can conduct flow through added wicking multifilament fibers, which develop matric suction that facilitates the drainage of water stored within an adjacent unsaturated soil mass. Such IPED geotextile is a wicking stabilization geotextile designed to have a water absorbent surface and enhanced drainage laterally within the planar structure of the geotextile. The unique manufacturing process of the wicking fibers in the IPED geotextile involves multiple steps that dramatically increase the specific internal surface area, a property that is responsible for the development of high matric suction of the wicking fibers. The wicking fibers will pull water from the surrounding soil, as well as provide a conduit for moisture along its channels. This increases drainage capability of the woven geotextile by facilitating moisture transmission along the inter-filament voids within the wicking fibers. Consequently, IPED geotextiles are capable of mobilizing in-plane flow under unsaturated conditions, while conventional geotextiles can only provide in-plane flow under saturated conditions. The structure of IPED geotextile also allows gravity-driven drainage through pore spaces created by the intersecting yarns, but only after the adjacent soil reaches saturation. In addition to in-plane flow capability, the IPED geotextiles with high tenacity yarns also serve as a reinforcement function.

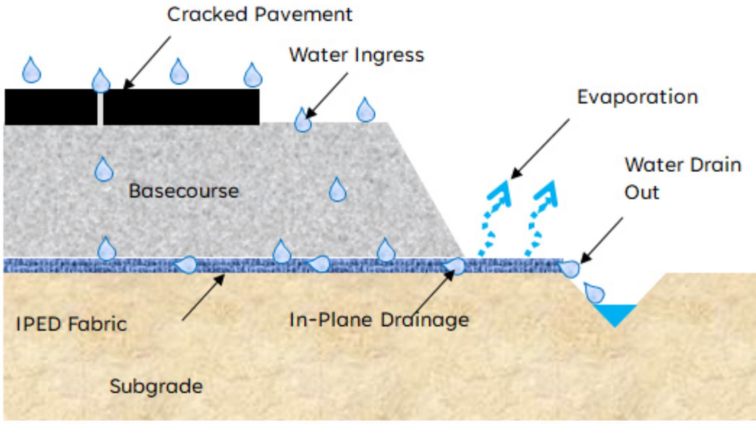


Figure 2 IPED geotextiles with enhanced lateral drainage capabilities in roadway systems.

3. ROAD REHABILITATION PROJECT

3.1 Project Description

A national highway No. 117 is the major highway connecting three provinces namely Nakhonsawan, Phichit, and Phitsanulok provinces in Thailand. This route serves as a secondary highway in Phitsanulok and Uttaradit provinces. The average daily traffic and the percentage of heavy trucks in 2021 are respectively 21,500 vehicles per day and 10 percent. The existing roadway was a conventional flexible pavement with four-lane divided carriage way: two-lane northbound (NB) and two-lane southbound (SB). The NB and SB were originally completed in 1976 and 1997, respectively. The highway was subsequently rehabilitated periodically since 2015. After the rehabilitation had been completed in 2021, the road pavement started experiencing severe damages. Some pavement distresses observed along highway No. 117 were longitudinal cracks, block cracks, alligator cracks, and rutting as shown in Figure 3. This roadway system was also seasonally impacted by flooding and considerable heavy traffic. Several routine and periodic maintenance strategies e.g. deep patching, pavement overlay etc. have been applied but the problem was still reoccurring. Such evidences clearly suggested that a traditional approach was not applicable for the existing condition.

Figure 3 Pavement distresses along highway No. 117.

3.2 Proposed Rehabilitation Method

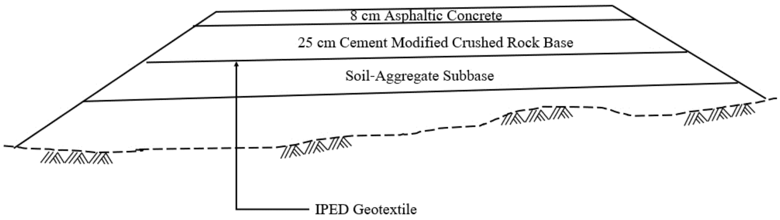
Several rehabilitation alternatives were considered to address all aspects of the problem. The key solutions of proposed rehabilitation method shall have three folds: (1) to maintain the elevation of the existing road pavement, (2) to enhance the layer homogeneity and uniformity as well as their structural integrity, and (3) to provide additional layer reinforcement and a separation function between new improved layer and existing or underlying problematic layer. The proposed solution shall eliminate the existing problems, minimize the impact of moisture damage due to flooding, prevent pumping of underlying fine-grained material, and improve load carrying capacity for over-loaded vehicles and increasing traffic volume in the future.

Based on the traffic information aforementioned, the expected traffic ESALs for the 15-year design period were approximately 10 million. According to the AASHTO (1993) design procedures, the required minimum structural number (SN) was 6.4. Therefore, a proposed pavement structure consisting of 80 mm asphalt surface, 250 mm cement modified crushed rock base, 300 mm soil-aggregate subbase, and 200 mm selected material was acceptable. In addition to this proposed pavement structure (SN ~ 6.6), the geotextile reinforcement with in-plane enhanced drainage (IPED) was also incorporated in the experimental section. An inclusion of IPED geotextile reinforcement was expected to improve the following performance: (1) enhanced lateral drainage of moisture migrating upward from a high groundwater level, (2) enhanced lateral drainage of moisture infiltrating downward from the surface, (3) enhanced layer stiffness and structural integrity, and (4) enhanced separation function between new improved layer and existing or underlying problematic layer.

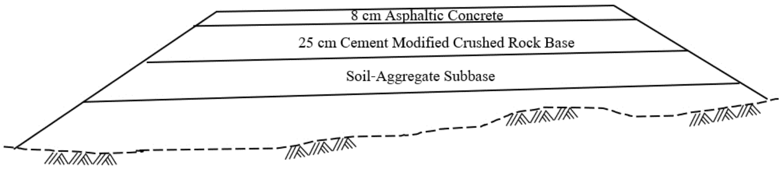
The IPED geotextile was made of very high tenacity polypropylene yarns having both cross-machined and machined directional tensile strength at 2% strain of 20 kN/m and 5% strain of 50 kN/m. The proprietary moisture wicking yarns were capable of removing excess moisture and dissipate it by capillary flow across the pavement under unsaturated soil conditions.

3.3 Trial Road Pavement Section

The Department of Highways by Nakhonsawan 1 Highway District, was responsible for the road rehabilitation project of national highway No. 117 (Nakornsawan-Nongtao). An experimental section of 1-km long located between Sta.14+000 and Sta.15+000 (LT) was proposed for a road research initiative project. This field trial was divided into two sections, e.g. with and without IPED geotextile, having 500-m long in each as shown in Figure 4. The project duration was 30 days, starting from September 24th to October 23th, 2022. A series of field instrumentation e.g. horizontal inclinometer, moisture sensor, suction sensor, rain gauge, data logger etc. was installed in these sections in order to monitor their in-service performance under the actual traffic loading and climatic conditions in Thailand. Figure 5 illustrates the layout of field monitoring instrument in this project.



(a) Section 1 with IPED geotextile (Sta.14+500 – Sta.15+000)



(b) Section 2 without IPED geotextile (Sta.14+000 – Sta.14+500)

Figure 4 Trial four-lane divided roadway section.

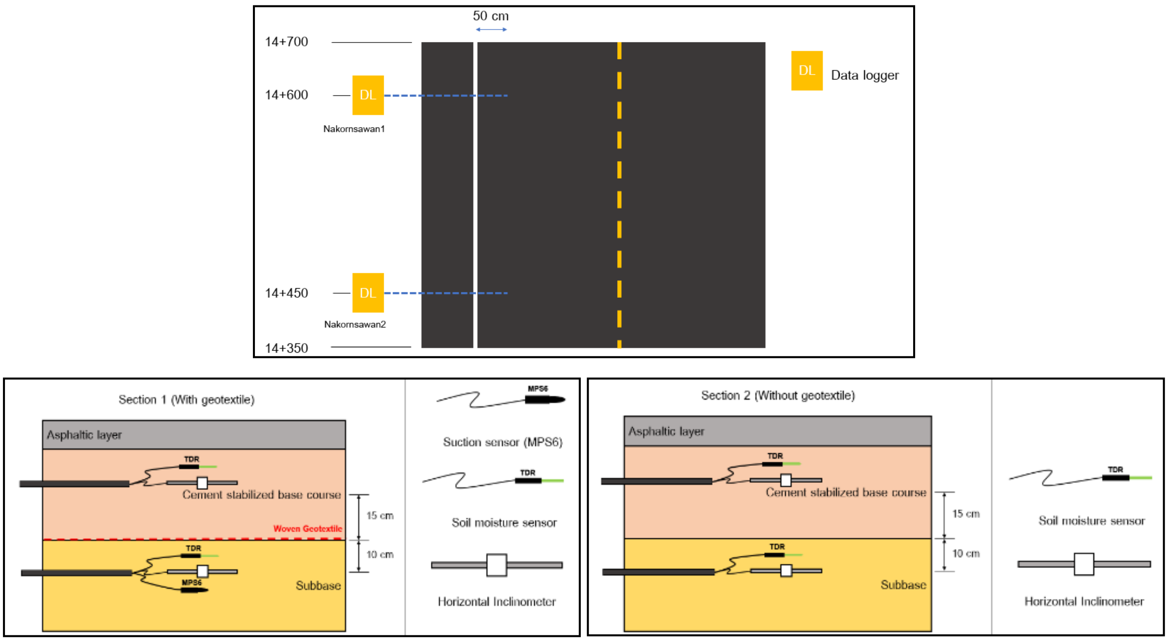


Figure 5 Layout of field monitoring instrument.

3.4 Rehabilitation Process

First, the existing asphalt surface and base course of 400 mm depth were removed by a milling machine. Followed by the placement and compaction of soil-aggregate subbase to meet the designed elevation. Field instrumentation for pavement performance monitoring and IPED geotextile were then installed as shown in Figure 6. After installation of field monitoring instrument and IPED geotextile, a loose crushed rock of 50 mm was placed for base levelling and mixture modification. The new crushed rock and cement powder were placed and mixed by a recycling machine to form the cement modified crushed rock or cement stabilized base. Such cement stabilized material shall meet the target unconfined compressive strength (UCS) of 2.4 MPa (24.5 ksc) – DH-S 213/2000 (Department of Highways, 2000). To avoid any damage to geotextile sheet, the mixing process by a recycling machine was carried out at a section without geotextile and then was hauled to the section with geotextile. The mixture was uniformly compacted to achieve the designed thickness of 250 mm and the target compaction level of at least 95% of modified Proctor density. The mix samples were also taken during the construction and was subsequently compacted for the laboratory UCS test – DH-T 105/1972 (Department of Highways, 1972). After the final elevation and compaction level of both sections had met the design specifications, the prime coat was applied and the asphalt surface was placed. Photos of the rehabilitation process and project completion are shown in Figure 7.

Figure 6 Installation of field monitoring instrument and IPED geotextile.

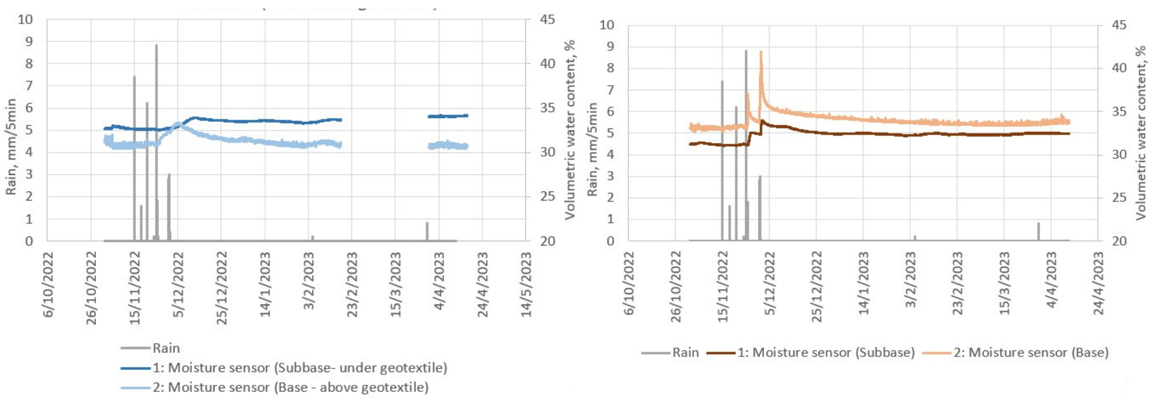
Figure 7 Rehabiltation process and project completion.

4. PERFORMANCE EVALUATION

A 100-mm-diameter cylindrical sample was collected from this site upon completion as shown in Figure 8. The cored sample showed continuity in a solid cylinder and good uniformity throughout asphalt surface and cement stabilized base. Results reflected an acceptable efficiency of construction machinery, process, and quality management of this project.

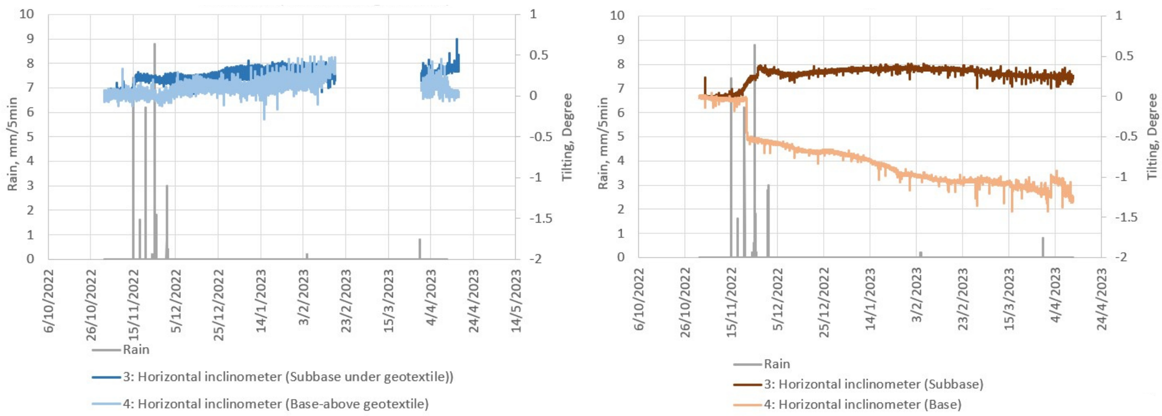
Figure 8 Extraction of a 100 mm diameter core.

Field monitoring data were collected for in-service performance evaluation as shown in Figure 9. The moisture data of the subbase layer in Section 1 with IPED geotextile (Fig 9a) were relatively constant regardless of the rainfall event, while the moisture data of both subbase and base layers in Section 2 without IPED geotextile (Fig 9b) exhibited an abrupt change approximately 1-2 days after the rainfall event. Nonetheless, the base moisture in Section 1 was only slightly increased due to the rainwater and was then decreased to its original value. The horizontal inclinometer data also indicated consistent response. Larger movement was observed in Section 2 without IPED geotextile (Fig 10b), while the movement in Section 1 with IPED geotextile (Fig 10a) was remarkably small during the rainfall event. Noted that the missing data was due to the robbery of cable and electrical wire at the site.



(a) Section 1 with IPED geotextile. (b) Section 2 without IPED geotextile.

Figure 9 Moisture data



(a) Section 1 with IPED geotextile. (b) Section 2 without IPED geotextile.

Figure 10 Movement data

Surface deflection measurement using the falling weight deflectometer (FWD) was conducted "before" and "after" rehabilitation and a comparison result is shown in Figure 11. It can be seen that the deflections reduced by approximately 20-30 percents after the rehabilitation in both sections. A pavement evaluation by visual inspection conducted several months after rehabilitation suggested that there was no sign of block crack and longitudinal crack. However, the asphalt rutting and alligator cracks were observed along the wheel path. These distresses were presumably associated with the pavement thickness design issue.

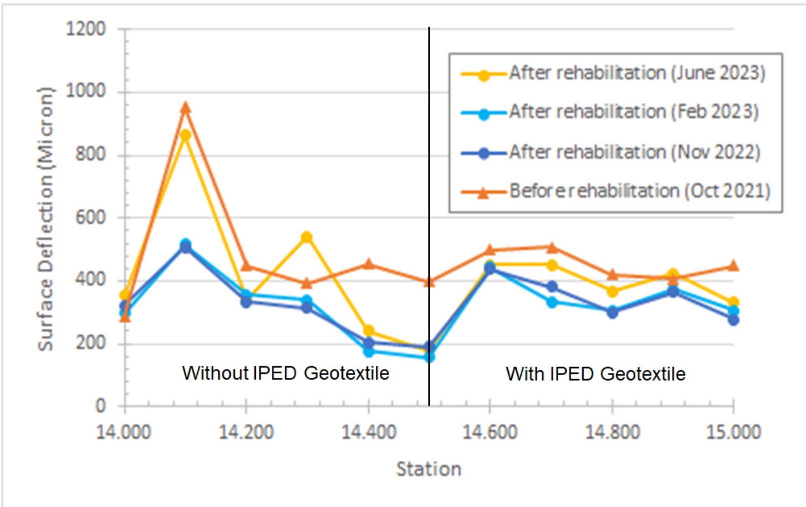


Figure 11 Comparison of FWD surface deflection data before and after rehabilitation.

Although, it is obvious that no longitudinal and block crack was observed in the experimental sections, cautions must be exercised in the pavement thickness design and the installation procedure when the IPED geotextile is to be used in the road pavement application as well as to assure its hydraulic performance for pavement resiliency.

5. CONCLUSIONS

After the major traditional rehabilitation strategies in 2021, a national highway No. 117 has been experiencing severe damages with some common pavement distresses e.g. longitudinal cracks, block cracks, alligator cracks, rutting etc. The roadway was seasonally impacted by flooding and considerable heavy traffic. To solve these problematic issues, the original pavement structure was redesigned and rehabilitated to make it more resilient to water- and traffic-related impacts. An experimental section incorporating the geotextile reinforcement with IPED showed no abrupt change in moisture and small layer movement during the rainfall event. Based on the empirical evidence, the experimental pavement section exhibited the following characteristics: (1) enhancing structural integrity by controlling layer stiffness, homogeneity, and uniformity, (2) incorporating layer reinforcement and/or drainage capacity by using IPED geotextile reinforcement, and (3) providing a good separator between new stabilized layers and the existing or problematic layer. It is expected that such rehabilitation approach can reduce the impact of extreme events, minimize moisture damage, prevent pumping of underlying fine-grained layer, and improve load carrying capacity for cement modified crushed rock or cement stabilized base that is subjected to the over-loaded vehicles and increasing traffic volume in the future. However, cautions must be exercised in the pavement thickness design and the installation procedure when IPED geotextile is to be used in the road pavement application as well as to assure its hydraulic performance for pavement resiliency.

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Examining Climate Change Impacts on Road Infrastructure in Archipelagic Regions: Risks, Scale, and Adaptation Measures in Indonesia's Road Development

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ABSTRACT

This paper examines the impacts of climate change on road infrastructure in archipelagic regions in Asia, focusing on Indonesia as a case study. With over 17,000 islands, Indonesia faces unique challenges and heightened vulnerability to climate change, including rising sea levels, frequent extreme weather events, and sudden flooding. By addressing overlooked aspects in current research, this study evaluates the specific effects of climate change on Indonesia's road infrastructure and highlights the uneven distribution of these impacts across the archipelago. The study employs a comprehensive methodological approach, including literature reviews and statistical analyses, to systematically identify and assess climate change events affecting road infrastructure in island nations. Using Geographic Information System (GIS) mapping techniques, national statistics from 2018 to 2023 are analyzed to visualize the risk distribution and scale of climate-related disasters. The analysis reveals the varied nature of climate change risks, making it difficult to devise comprehensive mitigation measures suitable for the diverse needs of different islands and regions. Differences in impact intensity between coastal and inland areas highlight the complexities in developing effective adaptation strategies. The study finds that existing national standards need improvement to address these complexities adequately. This paper emphasizes the urgent need for locally specific and nationally comprehensive measures to enhance the effectiveness, feasibility, and scalability of adaptation efforts. Such measures are essential to tackle the increasing disruptions caused by climate change on road infrastructure in Indonesia's expansive archipelago, thereby strengthening the resilience of road infrastructure in overall.

Keywords: climate change risks, adaptation, comprehensive planning, road infrastructure development, islands, Indonesia

1. INTRODUCTION

Archipelagic regions, characterised by interconnected islands, are susceptible to the impacts of climate change due to their complex geography and the associated challenges of managing diverse and dispersed landscapes. With over 17,000 islands, Indonesia represents a critical case study for examining the ramifications of climate change on road infrastructure. Each island and region within Indonesia presents unique challenges and vulnerabilities as it contends with climate change-induced disturbances, such as rising sea levels, recurrent extreme weather events, and abrupt flooding.

Climate change exerts a multifaceted threat to Indonesia's road infrastructure (Rachmawati et al., 2022). For instance, rising sea levels may lead to coastal erosion and saltwater intrusion, directly threatening coastal road networks and adjacent communities. Extreme weather events, including typhoons, exacerbate the risk of landslides and flooding, particularly in mountainous and low-lying areas. Sudden flash floods damage road surfaces, bridges, and culverts, disrupting essential connectivity and impacting economic activities (Zikra et al., 2015).

Despite the critical role of road infrastructure in ensuring mobility, economic development, and emergency response, more comprehensive research is needed to examine the specific impacts of climate change on roads in archipelagic contexts. Existing studies often focus on broader regional impacts or singular hazard assessments (e.g., Bappenas, 2021) without examining the spatial dynamics and differential vulnerabilities across Indonesia's archipelago.

This paper addresses this gap by investigating the effects of climate change on Indonesia's road infrastructure. It provides a nuanced understanding of the spatial dynamics and heterogeneous distribution of climate change impacts across the archipelago. For instance, low-lying coastal areas such as Jakarta and Semarang face risks from coastal flooding and erosion (Suroso & Firman, 2018), while inland regions like Kalimantan and Sumatra experience increased instances of heavy rainfall and landslides (Gernowo et al., 2012; Ruminta et al., 2018). Additionally, variations in the intensity of impacts between coastal and inland areas underscore the complexities of formulating effective adaptation strategies (Rachmawati et al., 2022). For instance, coastal defence measures may be necessary for some areas, while improved drainage and slope stabilisation measures may be more appropriate.

This study underscores the need for tailored, locally specific, and nationally comprehensive measures to bolster road infrastructure resilience in Indonesia. Such measures are essential to address the multifaceted challenges posed by climate change and ensure road networks' continued functionality and safety. Through this investigation, the paper contributes valuable insights into road infrastructure development and climate adaptation in archipelagic regions. The results can also formulate evidence-based recommendations for infrastructure planning and adaptation efforts for archipelagic regions.

2. CLIMATE CHANGE IMPACTS ON ROAD INFRASTRUCTURE AND ADAPTATION MEASURES

Archipelagic countries have extensive coastlines and diverse topography, making them particularly vulnerable to climate-related hazards (Leal Filho et al., 2021). Rising sea levels, increasing frequency and intensity of extreme weather events, and sudden flooding threaten the road infrastructure. These challenges necessitate a thorough understanding of the specific impacts of climate change on road networks within the archipelagic regions.

Sea Level Rise, Storm Surges, and Coastal Flooding

The rising sea level affects coastal erosion and inundation (de Abreu et al., 2022). First, it accelerates coastal erosion, undermining road foundations and leading to the collapse or damage of coastal roads (Lane-Visser & Vanderschuren, 2024). This event is particularly severe in low-lying coastal areas and smaller islands where land loss is critical (Monioudi et al., 2018). Second, permanent inundation of coastal roadways due to sea-level rise disrupts connectivity and accessibility, impacting local economies and disaster response capabilities. Critical road links, especially those serving ports and coastal communities, are at high risk.

Increased Frequency of Extreme Weather Events

More frequent and severe storms and typhoons directly damage road infrastructure. High winds and storm surges can erode road surfaces, wash away protective barriers, and cause structural failures (de Abreu et al., 2022). Furthermore, intense and prolonged rainfall can lead to waterlogging, weakening the road base and causing pavement deformation. In archipelagic regions with poor drainage, heavy rains exacerbate the problem, leading to frequent road washouts and landslides.

Storms and Sudden Floodings

Sudden, intense rainfall can cause flash floods, overwhelming existing drainage systems and submerging roads. This event disrupts transportation and causes significant damage to road surfaces and substructures, requiring costly repairs and maintenance (de Abreu et al., 2022; Lane-Visser & Vanderschuren, 2024). In addition, in areas where roads run parallel to rivers, overflow during heavy rains can flood adjacent roads. The sediment and debris carried by floodwaters further complicate recovery and repair efforts.

Climate Change Adaptation Measures

Academic reports suggest various measures to adapt to climate change impacts on road infrastructure development. The measures can be categorised into structural and non-structural. First, the structural measures include enhancing drainage infrastructure to handle increased rainfall and building coastal defences to protect road infrastructure from erosion and storm surges (de Abreu et al., 2022; Wan et al., 2017). Second, climate-resilient materials are utilised so that the infrastructure can withstand extreme weather conditions (PIARC, 2015) such as high-performance concrete, asphalt with improved binding properties, and corrosion-resistant metals. Third, construction techniques are performed to stabilise slopes and prevent landslides from disrupting the infrastructure (Wan et al., 2017).

The non-structural measures include many treatments. First, road development is avoided in floodplains and coastal zones (Shen et al., 2016; Suroso and Firman, 2018). Another example is conducting regular risk assessments and monitoring to identify vulnerabilities and prioritise interventions (Rachmawati et al., 2022). Third, regular maintenance schedules and retrofitting of existing infrastructure are performed (PIARC, 2015; Rathnayaka et al., 2023). The implementation of these measures depends on the context of the area where the road infrastructure is situated.

The following section will elaborate on the research methods to explore the impacts of climate change on road infrastructure in archipelagic nations by using literature reviews. From the results, we identified the extent to which such impacts have risked the road infrastructure development in Indonesia as the case study. The scale of impact exposure and the distribution were mapped out for assessment. National standards were identified to evaluate the ability to cope with climate events in Indonesia's road sectors. In the last section, from the analysis results, strategies for adapting to climate change impacts on road infrastructure is discussed.

3. RESEARCH METHODS

For the research methodology, this study conducted a literature review to synthesise existing research. Academic databases, Scopus and Google Scholar, were searched using relevant keywords such as "climate change," "road infrastructure," "archipelago," "sea level rise," "extreme weather events," "flooding", and "small islands", and other related terms. The review encompassed peer-reviewed journal articles, conference papers, organisations' reports, and technical documents. The literature review was not designed to be comprehensive but selective as considerable number of studies were found. The review focused on archipelagic regions in Asia where the impacts and adaptation capacities were relatively similar.

National Statistics from 2018 to 2023 detailing climate change-induced disasters, such as floods, landslides, and storms, were obtained from the Indonesian National Board for Disaster Management (BNPB). The data included information on the frequency, intensity, and geographical distribution of climate-related events across Indonesia. From the data, a spatial analysis involving Geographic Information System (GIS) mapping techniques was employed to visualise and analyse the distribution and scale of climate-related disasters across the archipelago. The evaluation of risk exposures was carried out by using the number of the climate impacts on road infrastructure with the scale magnitude of the events. Data from the Directorate General of Highways (2024) were used to for the analysis.

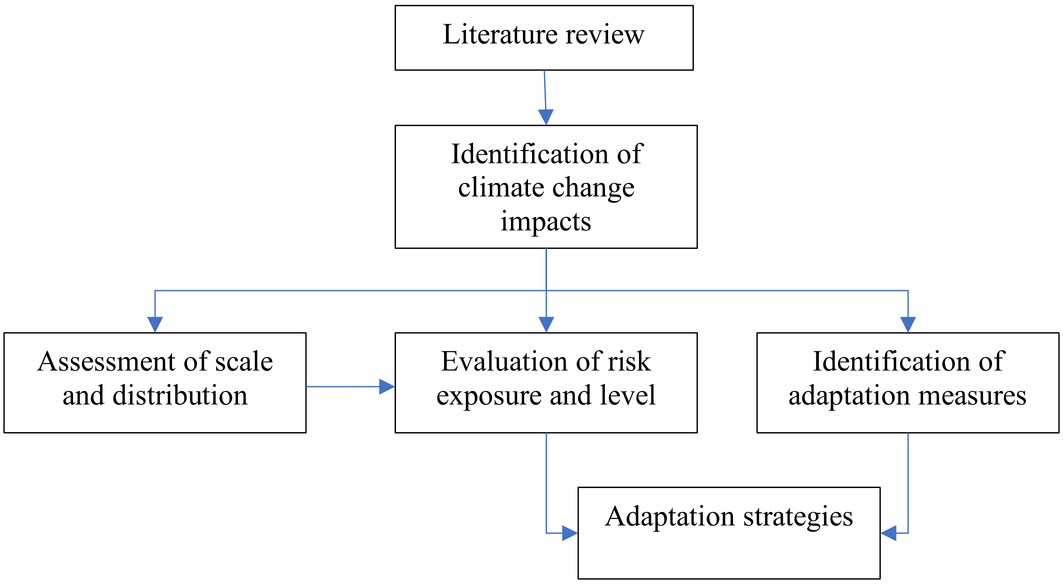

Figure 1. Research framework

Furthermore, national standards including technical guidelines for road infrastructure adaptation to climate change were reviewed and compiled. Based on the literature review's findings, these documents were categorised according to climate impacts, and the adaptation measures from the papers were evaluated. The research framework is depicted in Figure 1. Findings from the literature review, data analysis, and adaptation interventions from standards were integrated to provide a holistic understanding of the challenges posed by climate change to road infrastructure. The analysis allowed for the identification of gaps in existing adaptation capabilities and the formulation of recommendations for future research and policies.

4. RESULTS

Results – 1: Literature Review of climate change impacts

The geographical distribution and diverse topography of island nations compound the impacts of critical events. The literature reviews categorise the findings into three events impacting road infrastructure in archipelagic countries. These impacts include (1) sea level rise, storm surges, and coastal flooding, (2) increased frequency of extreme weather events, and (3) storms and sudden floodings.

Sea Level Rise, Storm Surges, and Coastal Flooding

The study by Lacambra et al. (2020) highlighted that rising sea levels in the Philippines, particularly in low-lying areas such as Manila Metropolitan, threaten coastal infrastructure. The infrastructures, including urban roads, are increasingly inundated. This inundation may lead to erosion, undermining the road foundation and increasing the frequency of repairs and maintenance. Research by Suroso and Firman (2018) documented how rising sea levels submerged coastal roads on Java's northern coast. The occurrence exacerbates maintenance and connectivity challenges (Triana & Wahyudi, 2020). The longest inundated primary arterial road stretches 8.14 km and is in Indramayu Regency (West Java Province).

Additionally, the primary arterial roads in Semarang and Demak have seen extensive road damage due to tidal flooding, experiencing coastal abrasion in several sections, such as along Kragan Road, with a length of about 400 m (Suroso & Firman, 2018). Brown et al. (2020) investigates that The Maldives, a low-lying archipelago, faces regular threats of road submersion due to rising sea levels, which affect the country's limited regional infrastructure, such as roads. Roads on islands like Hulhumalé are frequently flooded, disrupting daily activities and economic operations.

Increased Frequency of Extreme Weather Events

Fujii (2023) analysed the impact of climate changes, such as extreme weather, on road infrastructure in Japan, that note increased landslides and road washouts, particularly in Western Japan. Shimozono et al. (2020) analysed that recurrent typhoons had significantly damaged the coastal infrastructures. In regions like Kyushu, landslides triggered by heavy typhoon rains blocked the Kyushu Expressways in 2009, and some similar events cut off remote areas Ahmed (2015). Mikami et al. (2016) reported frequent typhoons and heavy rainfall, leading to severe road damage and disruptions. The 2013 Typhoon Haiyan, for example, caused extensive damage to roads on the Pan-Philippines Highway, the main road running along the northeast coast of Leyte Island. The damaged roads made transportation and relief efforts exceedingly tricky. Bridges like those in Leyte have experienced severe damage because of scouring, including abutment and pier footings. Moerwanto and Zulfan (2020) documented how frequent and intense weather events, such as storms and heavy rainfall, lead to landslides and road washouts, especially in mountainous and coastal regions of Indonesia. Regions such as Aceh and West Sumatra are particularly vulnerable, with landslides frequently severing road connections. Extreme weather also deteriorated roads due to rainwater inundation in Sleman-Yogyakarta in Indonesia (Pudyastuti & Nugraha, 2018).

Storms and Sudden Floodings

Moerwanto and Zulfan (2020) explored the impact of intense rainfall and flash floods on Indonesia's road infrastructure, especially in Jakarta and Borneo, where road surfaces are often submerged, leading to rapid deterioration. The frequent flooding in Jakarta results in significant economic losses due to road repairs and congestion (Pudyastuti & Nugraha, 2018). In Sri Lanka, Jayatilake and Abeysinghe (2020) found that intense rainfall and flash floods overwhelmed drainage systems, causing significant road damage and frequent need for reconstruction. The flooding disrupts road traffic in specific regions and extensive road networks because of delays, diversions, and partial or complete closure of roads (Abenayake et al., 2022). Meerow (2017) highlighted the frequent submersion of roads in low-lying areas such as Metro Manila during heavy rains, leading to extensive traffic disruptions. Flooding of major roads like Manila Metropolitan causes severe traffic delays and impacts the overall efficiency of urban transportation. More roads (around 158.9 km) in the Philippines will likely be flooded by inundation depths of 8 to 50 cm (Mikami, et al., 2016), causing high repair costs.

The findings have shown that climate change has impacted the construction and operation of road infrastructure in Archipelagic nations. Table 1 summarises the findings. The scale and distribution of the impacts, however, may vary. They are also found to be different across the subnational regions. Therefore, a detailed analysis should be done to specify adaptation measures for climate events in countries with a vast geographical context. The analysis in the next section will focus on the Indonesia context.

Table 1. Climate change impacts on road infrastructure in archipelagic nations from literature

Climate event	Impacts on road infrastructure
Sea level rise, storm surges, and coastal flooding	• damage to, or inaccessibility of, low-lying coastal road infrastructure • aggravated coastal flooding • increased dredging requirements • more frequent or intense flooding in low-lying areas • erosion of road base • erosion of bridge supports/bridge scouring • land subsidence
Increased frequency of extreme weather Events (e.g., extreme heat and rainfall events)	• increased pavement deterioration • reduced asset lifetimes and shorter maintenance windows of road infrastructure • thermal expansion of bridge joints
Storms and sudden floodings	• subsidence of infrastructure and roadbeds from increased aridity • flooding of roads • slope failures and landslides • roadway (including gravel and earth roads) washout • erosion and scouring or washout of bridges • increased sediment loading of drainage works • overloading of drainage systems • higher chances of infrastructure failure and disruption to operations • damage to catenaries, signs and lighting • increased tree-falling that may close roads

Source: summarised from literature sources

Results – 2: The distribution and scale of climate-related disaster affecting road infrastructure

The distribution and scale of climate-related disasters

The data regarding climate-related disasters has shown that Indonesia's archipelagic regions has been intensively impacted by climate change. During 2018 – 2023, the number of climate disaster events reached 16,022 across the regions. Drought and extreme weather are among the impactful disasters. The highest number of disaster events was in 2020, with the total number in that year being 1,468. Since then, the annual climate-related disaster has decreased. There are some possibilities regarding the decrease, such as better preparation in dealing with the disasters and mitigation efforts are already in place.

Table 2. Number of recorded climate-related disasters across archipleagic regions of Indonesia

No.	Climate-disasater events	2018	2019	2020	2021	2022	2023	Total
1.	Storm surge and coastal abrasion	0	0	90	55	25	22	192
2.	Slope disaster	642	723	1,159	1,027	887	405	4,843
3.	Floods	834	796	1,481	1,146	591	347	5,195
4.	Drought and extreme weather	1,117	1,392	1,468	838	651	326	5,792
		2,593	2,911	4,198	3,066	2,154	1,100	16,022

Source: compiled from BNPB (https://gis.bnpb.go.id/; last accessed: 15 June 2024)

In distribution, the coastal regions, including major urban centres in Java like Semarang (see Figure 2 (a)), exhibit high vulnerability to climate-induced phenomena such as coastal abrasion caused by storm surges. Areas in Sumatra have also shown multiple events caused by coastal erosion caused by the storms, particularly in small islands (see also Figure 2 (a)). Inland regions, such as Java and Sumatra (Figure 3(a) and Figure 2(b) respectively), have recently confronted different impacts, primarily heavy rainfall events and subsequent landslides in the period of 2018-2023. These hazards pose significant threats to road infrastructure, causing washouts, road blockages, and slope instability. Based on these illustrations, road infrastructure in Indonesia is prone to climate disasters. However, the impacts are unique across Indonesia. Coastal areas and smaller islands are particularly vulnerable to abrasion impacting the pavement structure, while some inland regions face less severe consequences with regards to sea level rise.

Figure 2. (a) storm surge and coastal abrasion

Figure 2. (b) slope disaster

Jakarta and Coastal Java in general have faced severe flooding and erosion problems with significant impacts on mobility along urban road networks. The regions in Sumatra and Sulawesi islands have experienced frequent landslides and storm damage that are more affecting on rural and intercity road networks than the urban parts. While, Eastern Indonesia has become isolated and less developed as the impacts on frequent floods in the period of 2018 - 2023. By looking at the number of drought and extreme weather events in the period, Southern Indonesia, particularly Java and Nusa Tenggara regions, show vulnerability to the events, with a consequence on the road operation in the urbanised areas.

Figure 3. (a) floods

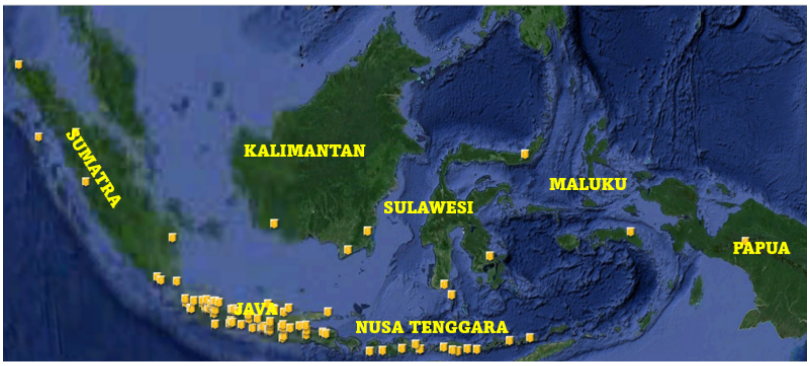

Figure 3. (b) drought and extreme weather

The climate change risks on road infrastructure development

The previous section has shown that the distribution of climate-related events on Indonesia's road infrastructure are multifaceted and widespread. Based on data from the Directorate General of Highways of Indonesia (2024), those events are exposed risks to road infrastructure development. These risks can be categorised into physical damage, economic and economic costs, and regional disparities (Table 3). The table shows that climate events have significantly impacted the accessibility of areas in the archipelago (82 incidents). The events have caused damage to roads, disrupting communities' mobility, particularly in remote areas. The damages also impact access to public services, such as healthcare units and schools. Economic losses are caused by the disruption of economic activities in both urban and rural areas (60 incidents). Another risk identified is physical damage to roads affected by floods and storms. Such events weaken structural integrity, leading to cracks, potholes, and erosions (39 incidents). The repair costs for rehabilitation have increased. Moreover, climate disasters pose safety concerns for road users because of road deterioration.

Table 3. Number of recorded main impacts of climate events on road infrastructure in Indonesia

No.	Main impacts	Frequency	Risks	Exposure based on distribution	Level of risks
1.	**Structural integrity**	39	• Floods and storms weaken the structural integrity of Indonesia's national roads, leading to cracks, potholes, and erosion. • The repeated submersion and drying cycles contribute to the rapid degradation of road surfaces.	All areas (both on mainland and coastal) (high exposure = 3)	High
2.	**Foundation erosion**	20	• Coastal and riverine roads are vulnerable to erosion. • Rising sea levels and storm surges erode the road foundations, leading to collapses and significant repair needs.	Mostly on coastal areas ((high exposure = 1)	Low
3.	**Increased repair and maintenance costs**	40	• The cost of repairing and maintaining road infrastructure after climate disasters is substantial. • The government has to allocate significant portions of its budget to emergency repairs, often at the expense of other developmental projects.	All areas (both on mainland and coastal) (high exposure = 3)	High
4.	**Economic disruption**	60	• Damaged roads disrupt transportation and logistics, affecting trade, tourism, and daily commuting. • This disruption has cascading economic effects, particularly in urban centres like Jakarta and Surabaya.	Mostly on mainland where the urban areas are located (high exposure = 1)	Medium
5.	Accessibility	82	• Damage to road infrastructure reduces accessibility, particularly for remote and rural communities. • This damage impacts access to essential healthcare, education, and markets.	All areas (both on mainland and coastal) (high exposure = 3)	High
6.	**Safety**	33	• Damaged roads pose safety hazards for motorists and pedestrians. • The risk of accidents increases significantly on roads compromised by potholes, landslides, or flooding.	Mostly on mainland (medium exposure = 2)	Medium

Source: compiled from field reports by Directorate General of Highways (2024).
Note: Risk level = Frequency * Exposure (> 100 = high, 50 – 100 = medium, < 50 = low).

Table 3 also indicates the level of risks on the infrastructure based on the frequency in the past and the risk exposures. The levels of climate disaster risks (high, medium, or low) are determined by the number of impacful events in the past multiplied by exposures based on the area's distribution. If all areas (both mainland and coastal) are impacted, then the risk level will be higher than other specific areas or only one area. Based on the indication in Table 3, weakened structural integrity, high repair and maintenance cost, and disrupted accesibility are those with significant risks in the Indonesia's context.

Results – 3: Climate change adaptation measures in national road standards

A review of existing national standards including technical guidelines was performed to evaluate the road authority's preparations in Indonesia to deal with climate change's impacts on road infrastructure. The evaluation in Table 4 identifies road elements targeted to adapt to the changing climate in the standards. Specific measures for adaptation were recorded from the evaluated documents. The evaluation result has shown that there are still gaps in measures compared with risks posed by the overall archipelagic regions. Specific adaptation measures to these elements, such as improved drainage systems, were proposed.

This study reveals that the application of these measures tends to focus on physical elements of roads, such as road materials, pavement structures, and bridges. Improvement in pavement design has been seen as a way to deal with the increased frequency of extreme weather events. Moreover, safety issues regarding the ability to improve pavement durability can be found in the design improvement. The road authority has already developed a monitoring system to inspect and inform whether particular road elements are still in good condition for operation. However, measures regarding the rise of sea level have been less developed. This finding can be understood as the focus not on adaptation but mitigation, such as re-routing of road networks. Some other measures can be added to the recent measures, such as nature-based solutions or structural approaches to slope disasters, such as mangrove reforestation for coastal protection, offering natural buffers against sea-level rise and storm surges. From Table 4, the road authority in Indonesia seem already prepared for coping with the impacts of climate change on road infrastructure as identified in Table 1.

Table 4. Measures in standards and technical guidelines to adapt to climate-affecting road infrastructure

No.	Climate events	Road elements in which standards are applied					Specific or targeted measures
		Road materials	Pavement structures	Bridge	Drainage systems	Slope/ embankment	
1.	Rising sea level	-	-	-	-	v	- Examination of embankment decay but not explicitly related to sea level rise
2.	Increased frequency of extreme weather events	v	v	v	v	v	- Flexible pavement design method based on changing weather conditions - Bridge inspection based on the analysis of river condition - Settlement limits on embankments where soft soils are found
3.	Sudden flooding	v	v	v	v	v	- Design of minimum thickness of embankment material and minimum height of subgrade above flood water level; - Inspection of river conditions of the bridges - Damage to the safety of embankments and foundations - Measurement of river flow discharge and open channels
4.	Soil erosion and landslides	-	v	v	v	v	- Application of structural and nonstructural mitigation for erosion and slope disaster:

No.	Climate events	Road elements in which standards are applied					Specific or targeted measures
		Road materials	Pavement structures	Bridge	Drainage systems	Slope/ embankment	
							- Inspection of river conditions of the bridges - Measurement of river flow discharge and open channels - Rapid inspection of drainage system condition and functions - Inspection of pavement, shoulders and embankments damaged because of dysfunctional drainage system.

Source: compiled from Directorate General of Highways (https://binamarga.pu.go.id/index.php/nspk)

The measures identified in Table 4 show the general standards to implement for adaptation measures. As found in Result-2, different regions in Indonesia have different challenges with climate change, such as urban vs nonurban (rural) areas or small islands vs main islands or coastal and inland regionas, so that a specific measure should be customised according to these regional disparities. Currently, no measures are targeted to particular regions to deal with the frequent climate risks. This study points to the need for more comprehensive solutions adaptable to local contexts but capable of addressing the specific vulnerabilities and the level of risks in Table 3. This handicap is still a challenge for Indonesia.

5. DISCUSSIONS AND CONCLUSIONS

The study highlights the regional disparities in climate change impacts on road infrastructure, with coastal and inland regions facing distinct challenges. Coastal areas are particularly vulnerable to sea-level rise and coastal erosion, while inland regions face heavy rainfall and landslides. The analysis reveals significant disparities in climate change impacts and levels of risks across different regions, complicating the provision of comprehensive adaptation measures suitable for diverse road development contexts. For example, the study finds that coastal regions are highly vulnerable to sea-level rise and storm surges, and inland areas face landslides and riverine flooding risks. The study also shows that assessing risk levels reveals that some impacts require attention, including maintaining road structural integrity, increased repairment costs, and disrupted accessibility (Table 3). With a vast archipelagic region, the road authority needs to concentrate on those impacts. Specific adaptation measures, such as coastal defence infrastructure and improved drainage systems, are also needed but should be adapted to specific local contexts. The study reveals different levels of risks as there are scalability gaps because of the impacts' distribution.

Some measures involve multiple sectors for a more comprehensive undertaking (Bappenas, 2021). Nature-based solutions, such as mangrove reforestation and polder constructions, emerge as promising approaches for coastal protection, offering ecological and socio-economic co-benefits (e.g., Zikra et al., 2015). However, challenges still need to be solved in scaling up these solutions. Mobilizing resources and institutional capacities is required to mainstream climate change into regional planning and development (Uittenbroek et al., 2014). In conclusion, this study underlines the need for robust road policy frameworks to support effective adaptation measures in archipelagic regions. The focus on enhancing overall road construction needs to be improved but on specifying the measures and the context. A shared responsibility between local and national actors can be the key to success.

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Predicting Highway Flood Risk in Thailand using Machine Learning

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ABSTRACT

In response to the increasing problem of floods damaging Thailand's highways and causing widespread disruption, this work offers a new tool for assessing the likelihood of highway flooding, leveraging Machine Learning (ML). The core of the analysis is integrating various datasets: historical rainfall data, historical national highways flood level data, and Thailand weekly rainfall forecasted data. This integration is achieved through Random Forest (RF) and Artificial Neural Network (ANN) models. By predicting the severity of flooding events, we hope to significantly improve disaster preparedness and decision-making for highway users and infrastructure managers. This can be achieved by implementing real-time alert systems on highway networks. These systems would utilize flood forecasts to warn drivers about potential dangers and allow them to make informed decisions, such as avoiding flooded routes. Additionally, highway authorities can take proactive measures such as deploying emergency response teams or closing vulnerable sections in advance. To systematically minimize future disaster risks, the study recommends establishing a highway network alert system. This system would disseminate real-time flood warnings to regional authorities through a dedicated portal on the Highway Disaster Management System (HDMS) website. Both categories of ML algorithms demonstrate strong predictive abilities for anticipating flood levels. The ANN model could be integrated into existing HDMS, DOH

Keywords: Machine Learning, Random Forest Regression, Flood-level forecasting, Disaster risks, Highway network

1. INTRODUCTION

Thailand faces risks from floods and public disasters, which have become more frequent and severe, causing significant damage to lives and property. These disasters result from both natural and anthropogenic causes. At the same time, some parts of the highway network in the northern and southern regions of Thailand experience recurring floods, affecting safety and causing loss of property for commuters travelling on these routes (Chullabodhi, 2024). Recent studies have shown the potential of using ML techniques to forecast flood risk and support infrastructure resilience (Tachaudomdach, S. et al., 2021).

The Bureau of Highways Maintenance Management (BHMM), Department of Highways (DOH), has studied and developed a RF model to predict flood levels on Thailand's highway network. This study will leverage two ML algorithms - RF and ANN - to predict the likelihood and severity of highway flooding based on the available data. Therefore, both methods are employed to estimate trends for the 7-day upcoming floods, incorporating independent variables to predict flood levels; those are, historical rainfall data, historical national highways flood level data, and Thailand weekly rainfall forecasted data.

In order to enhance disaster preparedness, the researcher created a model to estimate the potential impact and seriousness of floods on the highway network. Furthermore, the model seeks to assist DOH personnel and other relevant officials in devising strategies or actions to address and prevent future floods.

1.1 Objectives

This research has objectives:

- To predict flood levels on road surfaces in the highway network using ML and evaluate the model's performance.
- To support DOH personnel in preparing machinery and manpower, implementing preventive measures, and managing floods on road surfaces.

1.2 Scope of research

This research has the following scopes:

- The study area covers the highway network throughout Thailand, encompassing a total of 1,530 routes with a total road length of 51,925.81 kilometers, as shown in Figure 1.

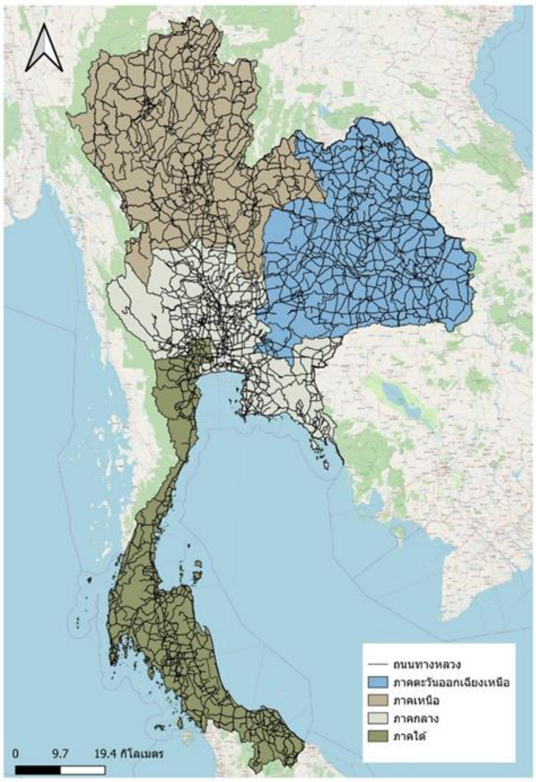

Figure 1. Map of Thailand's road network.

Predictions of flood levels on the road surfaces of the highway network were determined by examining the correlation between historical rainfall data, historical national highways flood level data, and Thailand weekly rainfall forecasted data. The analysis did not take into consideration other factors that could result in flooding, such as runoff, human activities, and flash floods.

2. LITERATURE REVIEW AND DATA SET

2.1 Random Forest (RF)

Random Forest is a ML algorithm which enables computers to learn autonomously. It has capability in both classification and regression tasks (Breiman, 1996). In regression, it employs decision trees to predict continuous values, thus enhancing the accuracy of final outcome predictions.

In RF, the key concept is to produce a variety of decision trees (ranging from 10 to over 1000 models). While each tree receives distinct training data, their combined predictions should be similar. Subsequently, the algorithm determines the mean or median based on the output of each decision tree for a regression task (Janthongpoon, 2022), as depicted in Figure 2. An increase in data is expected to enhance the accuracy of the model's predictions.

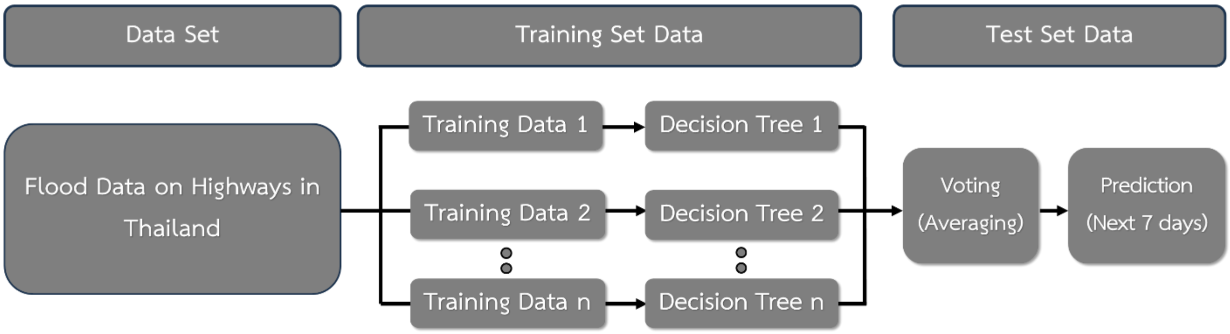

Figure 2. Random Forest process (Chullabodhi, 2024).

Nevertheless, it is crucial to be aware of potential pitfalls or limitations in model building. One of the main concerns is to confirm that the data values show variability in line with the decision tree and avoid outliers that significantly differ from the other values. Such discrepancies could adversely affect the accuracy of predictions. Hence, it is recommended to implement a data preprocessing prior training the model.

2.2 Artificial Neural Network (ANN)

ANNs are proficient mathematical systems that employ parallel processing effectively, enabling them to replicate the structure of biological neural networks with interconnected neuron units. ANNs are esteemed as the most popular learning algorithms within the realm of ML, acknowledged for their versatility and effectiveness in modeling complex flood processes with a high level of fault tolerance and accurate approximation (Abbot & Marohasy, 2014). ANNs have demonstrated their effectiveness in modeling complex, nonlinear relationships inherent in hydrological and transportation systems (Chikaraishi et al., 2020).

The architecture of ANN typically consists of an input layer, one or more hidden layers, and an output layer as depicted in Figure 3. The weighted sum of the inputs arriving at each neuron generates an output signal through an activation function (Xing et al., 2017). The hidden layers are responsible for extracting and learning the features from the input data, while the output layer produces the final predictions. The input layer of the ANN architecture is responsible for receiving data from various sources. Accordingly, the number of neurons in the input layer is determined by the number of input data sources. The data is then actively processed through the hidden and output layers of the network. The appropriate number of hidden layers as well as the number of neurons in each hidden layer are frequently established through an experimental, iterative approach. The training process of the back propagation (BP) in ANN involves adjusting the weights of the connections between neurons to minimize the error between the predicted and actual outputs (Yeh, 1998).

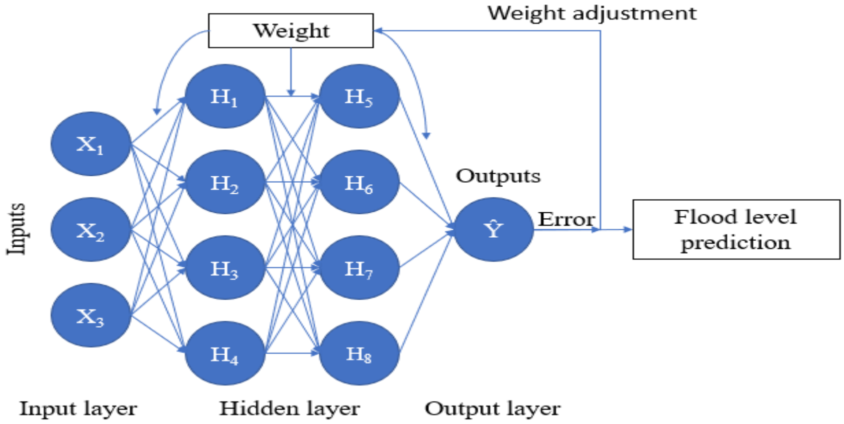

Figure 3. ANN process with BP algorithm.

3. DATA AND METHODOLOGY

3.1 Data set

3.1.1 Historical rainfall data

The historical rainfall data is meteorological information sourced from the Smart Water Operation Center (SWOC), Royal Irrigation Department (RID), the Ministry of Agriculture and Cooperatives (MAC), which provides rainfall quantities per province in millimeters (mm.).

3.1.2 Historical national highways flood level data

The historical national highways flood level data is information regarding the vertical height of stagnant water on the road surface. This data was obtained from reports by DOH officers who measured water levels at midpoints of road in centimeters (cm.), as shown in Figure 4. These reports are then collated through the HDMS, DOH.

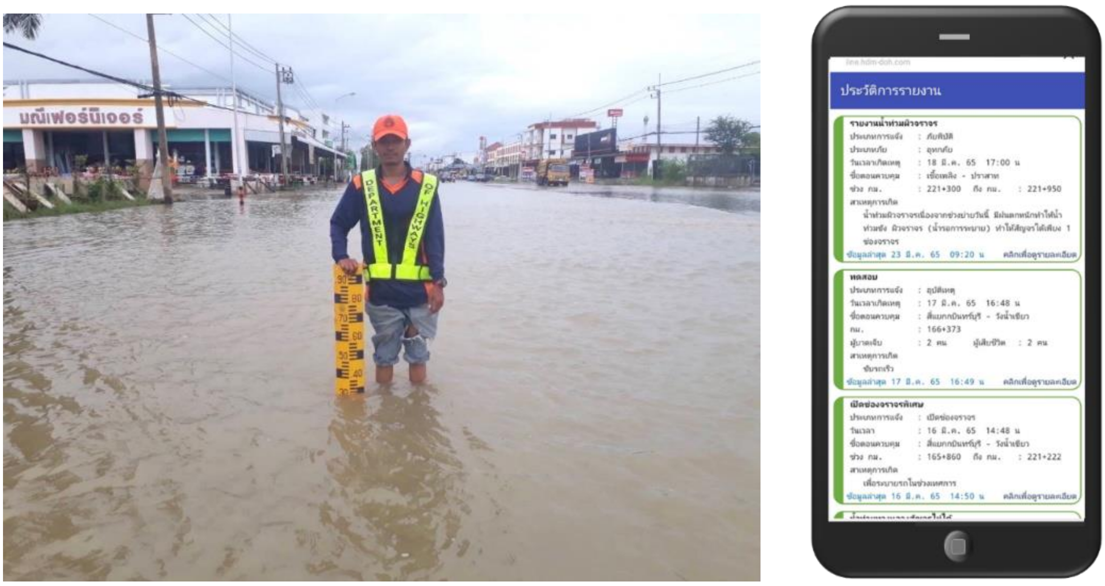

Figure 4. DOH officer measures flood level at midpoint of road.

3.1.3 Thailand weekly rainfall forecasted data

The Thailand weekly rainfall forecasted data was introduced from the Meteorological Information System (MIS) through the Application Programming Interface (API), sourced from the Thai Meteorological Department (TMD), Ministry of Digital Economy and Society (MDES). This data was a result of weather monitoring and forecasting Thailand weekly rainfall, which accumulated weekly rainfall data in Thailand (forecasted weekly rainfall in mm.) and were in Comma-Separated Value (CSV) format. When integrating this data with the QGIS software, it needs to be presented in raster format using the Inverse Distance Weighting (IDW) technique. This process involves image processing (Wijithanasarn, 2022), as illustrated in Figure 5.

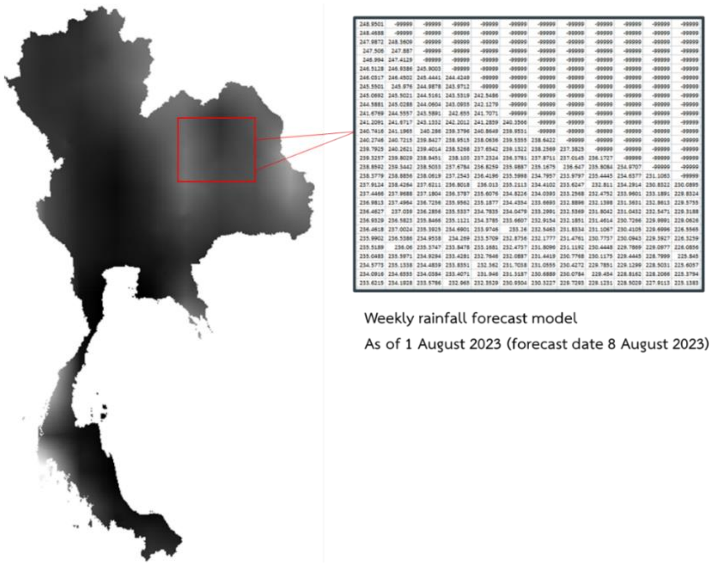

Figure 5. An example of the 7-day forecasted rainfall model.

By reviewing relevant research and literature, the researchers developed models to predict flood levels on Thailand's highway network, the inputs of models were presented in Table 1.

Table 1. Sources of data used to develop model.

No.	Data	Source
1	Historical rainfall data	SWOC, RID
2	Historical national highways flood level data	HDMS, DOH
3	Thailand weekly rainfall forecasted data	MIS, TMD

3.2 The Highways Disaster Management System (HDMS)

BHMM has created the HDMS to enhance disaster management efficiency. This system is used for reporting incident's status or disasters through HDMS' LINE Official Account and the website of the Disaster Management Center, BHMM, DOH. It serves as a tool to support the operations of DOH central and regional officers during emergency or disastrous incidents. Officers are capable of informing about incidents on highway such as floods, storms, landslides, wildfires, and road closures. Additionally, the system can analyze and assess disaster risks on highways, providing alerts on the risk of areas with recurring floods, historical peak water levels, and current water levels. This information is summarized and presented through the system's dashboard, which can display overall reporting, incidents tracking, risk information in various types of maps useful for disaster management. The system's display is illustrated in Figure 6.

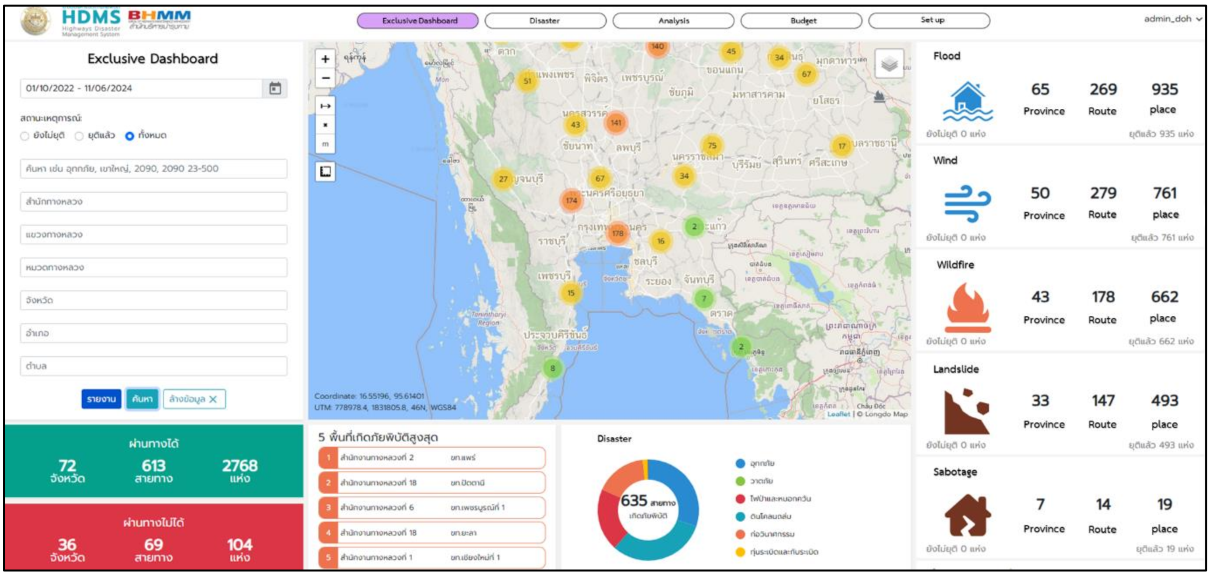

Figure 6. The HDMS' dashboard summary the current situation on highway network.

3.3 Flood level prediction process

The process began with collecting independent variables used for flood level prediction, including historical rainfall data, historical flood levels on national highways, and Thailand weekly rainfall forecasted data. These data were preprocessed before being analyzed training the RF and ANN to predict the flood levels on the highway networks. Lastly, the predicted data from the model was compared with the actual flooded levels, completing the prediction process, illustrated in Figure 7.

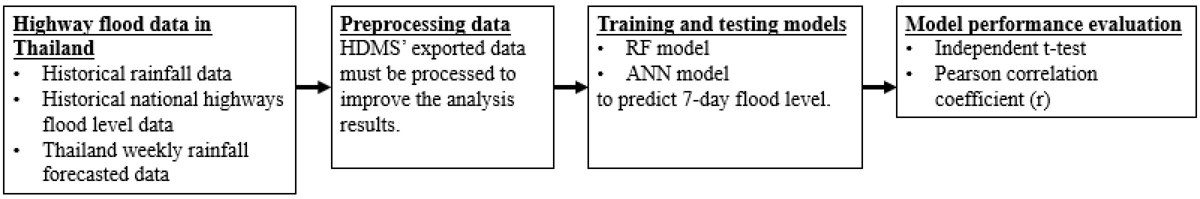

Figure 7. Flood prediction process.

3.3.1 Preprocessing data

Prior to training the models, researchers reviewed the data exported from the HDMS to enhance the analysis results. The data was categorized by disaster types, correlating water level data were verified with actual images to excluded inaccurate or false reports from the analysis.

3.3.2 Training and testing the models

The models were trained by three independent variables; which were historical rainfall data, historical national highways flood level data, and Thailand weekly rainfall forecasted data from the MIS, TMD with the details as follows:

- Historical rainfall data: This is the volume of rainfall in millimeters at each route, control section, and kilometer posts on the highway networks. Where the segments are located in a specific province, the rainfall data for that area was used.

- Historical national highways flood level data: The data from October 2022 to July 2023 (9 months) as training data, and additional data will be collected as cumulative data if forecasts were made in subsequent months, as shown in Figure 8.
- Thailand weekly rainfall forecasted data: This data was derived from weather measurements and forecasting from the Thailand Weekly Rainfall system, the MIS, DWR providing weekly rainfall forecasts.

1st — Training — Testing

2022	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2023	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec

2nd — Training — Testing

2022	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2023	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec

3rd — Training — Testing

2022	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2023	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec

4th — Training — Testing

2022	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2023	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec

5th — Training — Testing

2022	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2023	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec

6th — Training — Testing

2022	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2023	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2024	Jan											

Figure 8. The training and testing data used to build ML model to predict highway flood levels.

3.3.2.1 Training RF model

The initial steps of the RF model involve randomly selecting data from the entire dataset and constructing decision trees to derive predictions. Subsequently, a predetermined number of trees is picked for decision-making, and this random selection process, paired with forming decisions from data samples, is reiterated continuously to train the data. Before predictions can be made, the predicted values are derived from the decisions of each tree. Regression analysis uses the averaging method to forecast flood levels on highways by averaging predictions from all trees (Bureau of Highways Maintenance Management 2023). The process is illustrated in Figure 9.

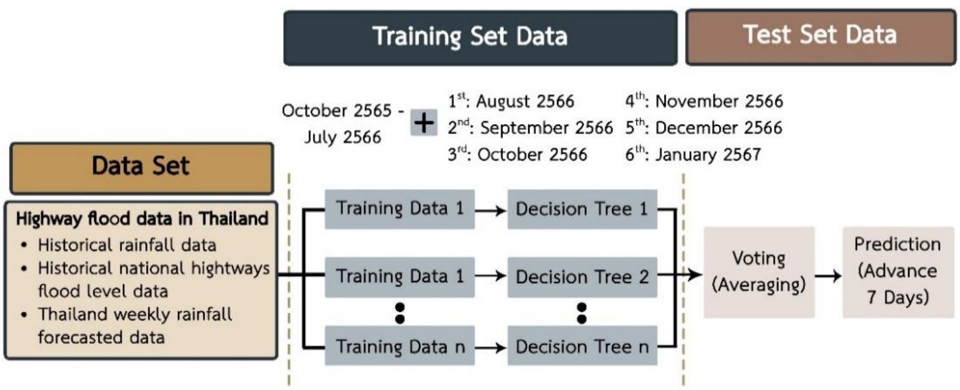

Figure 9. RF process.

3.3.2.2 Training ANN model

The same independent variables for RF have been utilized for development of ANN model to predict a 7-day predicted flood level on the highway network. Multiple network structures with distinct hidden neuron quantities undergo training and assessment. The neural network learned using BP algorithm and the rectified linear unit (Relu) was chosen as transfer function in hidden layers. By analyzing the performance measures obtained during testing, the best performance network architecture for the ANN model was identified. Table 2 contains the neural network architecture parameters for the ANN model.

Table 2. ANN architecture parameters for flood forecasting model.

ANN	
Number of input neurons	3
Number of hidden neurons	8
Number of hidden layers	2
Learning rate	0.01
Transfer function of hidden layer	Relu
Transfer function of output layer	Linear
Training algorithm	BP
Optimizer algorithm	Adam
Batch size	32
Training cycles, epochs(e)	100

3.4 Model performance evaluation

After obtaining data from the flood level forecast model and the actual flood occurrence reports through the HDMS, the accuracy of the ML model was assessed using statistical principles. This evaluation involved using the following methods:

- **The Independent t-test method**

Statistical testing of two independent groups using the independent t-test method, under the hypothesis that the combined variance is equal but unknown. This involves comparing the means of quantitative variables between two independent sample groups, performing a two-tailed test with a confidence level of 95% (alpha value of 0.05) (Phonprasertmanit, 2015). The hypotheses are as follows:

$H_0: \mu_{model} = \mu_{actual}$: The mean flood levels from the model and the reported actual flood levels through HDMS are **equal**. (1)

$H_1: \mu_{model} \neq \mu_{actual}$: The mean flood levels from the model and the reported actual flood levels through the HDMS are **not equal**. (2)

Once the calculation of the aforementioned parameter is completed. If the p-value > α, we accept H_0 or the experimental hypothesis as true. However, if the p-value < α, we reject H_0 and accept H_1. A low p-value indicates that the observed data are unlikely under the null hypothesis whereas high p-value suggests that the observed data are consistent with the null hypothesis.

- **Pearson Correlation Coefficient (r)**

Correlation analysis is a widely used statistical method for assessing the strength and direction of the linear relationship between two variables (Falk & Well, 1997). The Pearson correlation coefficient, denoted by r, is the most commonly used measure of correlation (Schober et al., 2018). In the context of ML, correlation analysis can be employed to evaluate the accuracy of predictive models by examining the relationship between the predicted values and the actual, observed values (Gupta et al., 2022) (Pratama et al., 2021). A value of r close to 1 indicates a strong positive linear relationship, while a value close to -1 suggests a strong negative linear relationship. The test of Pearson Correlation Coefficient (r) is shown in Equation 3 and its interpretation is summarized in Table 3.

$$r = \frac{\sum(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum(x_i - \bar{x})^2 x \sum(y_i - \bar{y})^2}} \tag{3}$$

Table 3. A table illustrates the meaning of the parameter values.

Parameter	Value	Interpretation
r	> 0.8	Very high positive correlation
	0.6 - 0.8	High positive correlation
	0.4 - 0.6	Moderate positive correlation
	0.2 - 0.4	Low positive correlation
	< 0.2	Negligible correlation

3.5 Model performance evaluation

After completing the flood level prediction on highways in Thailand using RF and ANN, the model's performance will be evaluated using two evaluation approaches as follows:

- The Independent t-test method
- Pearson Correlation Coefficient (r)

If the model meets the criteria for all the above parameters, it indicates that the RF and ANN model performs prediction accurately.

4. RESULTS

4.1 HDMS output page displaying flood level prediction

The system output reveals flood forecast data for 7 days in advance, which evaluated from the RF model on highway networks in the HDMS, as illustrated in Figure 10 and 11.

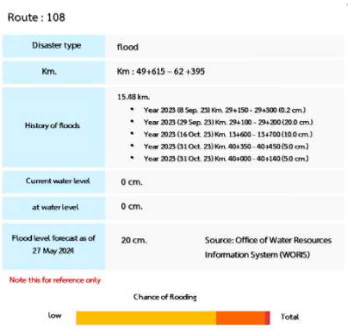

Figure 10. An example of a flood level prediction page on 20th May 2024

(predicted on 27th May 2024).

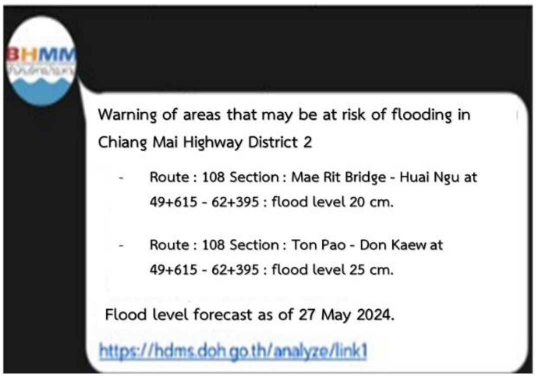

Figure 11. An example of alert officials to watch out for flooding on 20th May 2024 (Predicted on 27th May 2024).

4.2 Model performance evaluation results

In this study, basic statistical principles used to evaluate the model's performance include the Pearson Correlation Coefficient (r), Independent t-test method, and then compare the actual flood location predicted by the model with the floods obtained from the model. Higher accuracy is achieved with a larger amount of collected data, demonstrating the validity of the study's hypothesis. This means that increasing the amount of training data will result in more accurate model predictions. The model's performance evaluation showed that the model's accuracy score is at a good level, indicating that the prediction results from the model are quite accurate as shown in Table 4 and Table 5.

Table 4. RF model accuracy validation.

Month, Year	Sample (N)	r	p-value	α	Result
August 2023	1,312	0.89	0.42	0.05	Accept H_0
September 2023	1,364	0.87	0.51	0.05	Accept H_0
October 2023	1,586	0.86	0.08	0.05	Accept H_0
November 2023	1,811	0.89	0.12	0.05	Accept H_0
December 2023	1,915	0.88	0.17	0.05	Accept H_0
January 2024	2,031	0.86	0.09	0.05	Accept H_0

Table 5. ANN model accuracy validation.

Month, Year	Sample (N)	r	p-value	α	Result
August 2023	1,312	0.87	0.61	0.05	Accept H_0
September 2023	1,364	0.89	0.70	0.05	Accept H_0
October 2023	1,586	0.9	0.15	0.05	Accept H_0
November 2023	1,811	0.86	0.26	0.05	Accept H_0
December 2023	1,915	0.91	0.14	0.05	Accept H_0
January 2024	2,031	0.87	0.11	0.05	Accept H_0

4.3 Comparison of actual flooding locations with predicted locations

The predicted flood locations from RF and ANN model were plotted against the actual flood locations, extracted from HDMS, over a six-month period (from August 2023 to January 2024), to assess the model's performance by comparing the overlapping flood locations. The amount of data for each month is summarized in Table 4 and 5. These plots suggest that the RF and ANN models are adequately predicting the occurrence of flood on highway network since the predicted locations from the model significantly overlapping with the actual flood locations, as exemplified in figure 12 and 13.

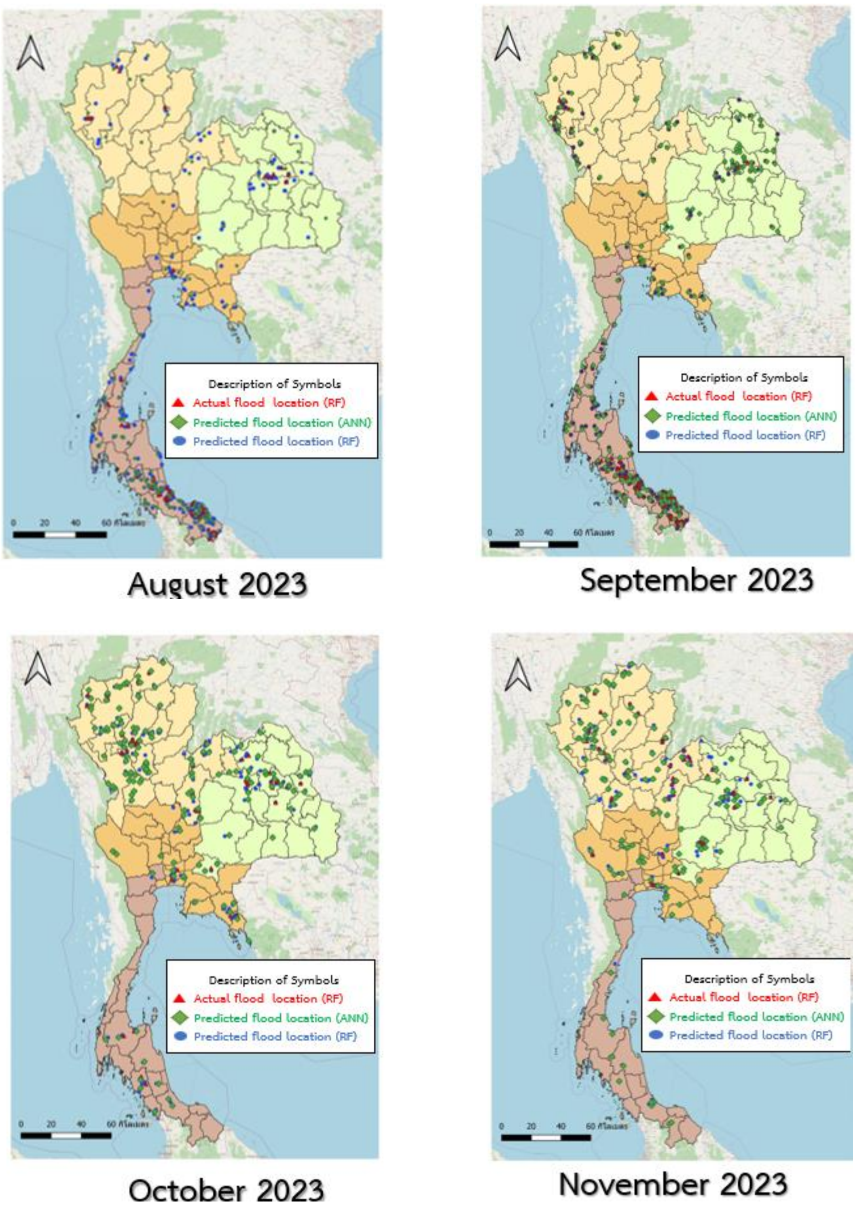

Figure 12. Regions actual flooding locations with model predicted locations (RF and ANN) from August 2023 to November 2023.

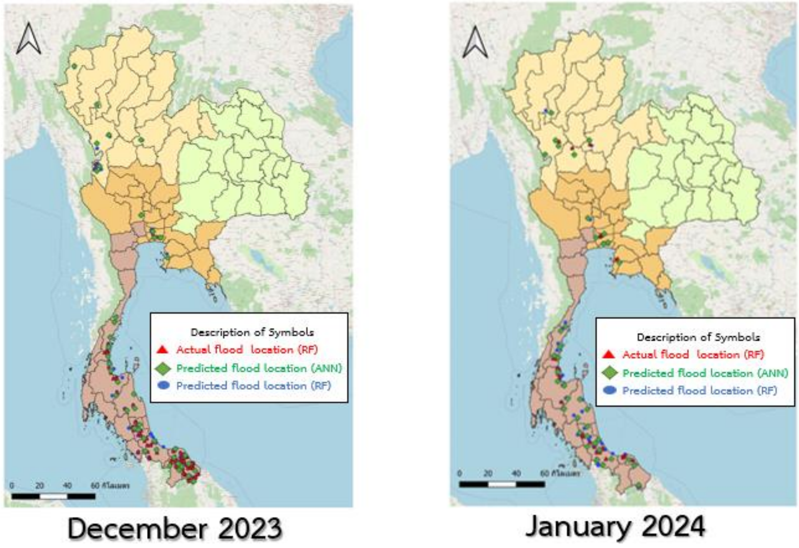

Figure 13. Regions actual flooding locations with model predicted locations (RF and ANN) from December 2023 to January 2024.

5. CONCLUSIONS AND RECOMMENDATIONS

The RF and ANN models have an ability to predict flood levels on highway networks with high accuracy for the same input data. The analysis uses three independent variables: historical rainfall data, historical national highways flood level data using data, and Thailand weekly rainfall forecasted data from October 2022 to July 2023. These collections of data were used as the training data for predicting flood levels in total of six-month period (from August 2023 to January 2024). Additionally, the performance of the flood prediction model was evaluated using statistical technique by comparing model predicted data with the actual flood reports from the HDMS. The results showed that the parameters, including the Pearson Correlation Coefficient (r) and the independent t-test analysis, passed the criteria in each month. This indicates that the flood prediction models for highway networks are accurate and precise, with consistent data. As more data is added cumulatively to train the models, the accuracy of the predicted results can be achieved. The results let to the conclusion that both RF and ANN model are practical for predicting flood levels on national highways. The ANN model could be integrated into existing HDMS, DOH. When compared to more advanced models, ANN is favored for its simplicity. In situations where there is a lack of data, artificial neural networks prove to be the most efficient method for predicting floods.

5.1 Parameter settings

The selection of parameters for the study must be chosen according to parameter selection techniques, such as using correlation analysis (with correlation coefficient) to identify the parameters most related to the study's outcomes. For instance, it is essential to determine whether to use a classification model when the correlation coefficient is close to zero or a regression model when the correlation coefficient is close to one.

5.2 Model accuracy

The research demonstrates the model's performance and accuracy, which can be further developed in the following years. This will aid in analyzing and identifying risk locations or areas prone to flooding on the highway network to prepare for potential floods. The underlying assumption is that increasing the training data will enhance the model's prediction accuracy.

6. ACKNOWLEDGMENTS

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Assessment of Seismic Performance Level of Bridge in Indonesia Based On Geometric Parameter Analysis of Earthquake Resisting Element

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ABSTRACT

In Indonesia, lateral loads due to earthquakes in bridge design are generally very significant. Regarding this, it is critical to be aware of Earthquake Resisting Elements (ERE), which are element that provide resistance against earthquakes. This study uses a fragility curve to illustrate seismic vulnerability, which was created using pier geometry changes as an ERE. Midas Civil created computational models of the bridges based on finite elements, which were then examined using non-linear time history analysis (NLTHA) to determine the derivation of fragility curves. The findings indicate that pier geometry has a substantial impact on the fragility. More specifically, the significant rate of change in the intensity measure (IM) indicates that a taller pier is more susceptible to seismic activity. $IM_{collapse}$ for h_{pier} = 13,2 m is approximately 1,5 g while $IM_{collapse}$ for h_{pier} =7 m is approximately 1,2 g for chance of exceedance >50% (complete damage). It is possible to conclude that two times increase in h-pier leads in an $IM_{collapse}$ difference, up to 0,3-0,4 g. The fragility curve of the bridge with higher pier is steeper, indicating that it was more vulnerable. This preliminary parametric seismic analysis approach can be efficiently used for further seismic evaluation and development of design concepts of newly built structures.

Keywords: Earthquake Resisting Element, Fragility, NLTHA, Pier Height, Vulnerability

1. INTRODUCTION

In designing bridge constructions resistant to earthquakes, it is vital to keep in consideration that besides a large-scale earthquake may cause partial collapse of the structure, smaller and medium-sized earthquakes will generally cause the structure to behave within elastics bounds and cause no major damage. Bridges built using the earthquake resistant structural design technique are often designed to be inelastic to the Design Basis Earthquake (DBE), but linearly elastic to gravity loads, temperature, and wind. In Indonesian bridge design, lateral loads resulting from earthquakes are typically highly large and have a higher effect than other lateral loads. Allowing for the building to behave inelastically in the event of a big earthquake is one way to lessen the force demands caused by earthquakes. Plastic hinge formation can cause the bridge to sustain damage up to a certain limit. Given that earthquake resistant bridges highlight structural ductility and effective seismic energy dissipation capabilities, this needs to be followed by good detailing ((AASHTO, 2020). Furthermore, referring to the latest NCHRP 949 - Performance-Based Evaluation, the performance requirement is "Life Safety" for a hazard 1000-year seismic load.

A comprehensive understanding of the factors that influence the seismic behavior of bridges is crucial to reduce the risk of catastrophic failure, ensuring the safety of people and infrastructure during an earthquake (Thakkar, *et al.*,2023). The seismic vulnerability of bridge structures depends on several aspects of structural form such as whether single or multi-span, continuous or simply supported. The seismic susceptibility of a bridge structure is further influenced by the pier height, span length, amount of confinement, age of the structure, and soil condition (Simanjuntak, V.C, et al., 2023).

In relation to this, it is essential to pay be aware of Earthquake Resisting Elements (ERE), which are factors that offer earthquake resistance and are governed by the 2011 AASHTO Guide Specification for LRFD Seismic Bridge Design. As focus of study, the pier element as ERE will be varied in geometry, and the fragility curve will show how seismically vulnerable each variation model is. In probabilistic seismic risk assessment of highway bridges, the fragility curve, a correlation between the probability value of a particular degree of damage happening in a structure and the associated earthquake intensity level, has found broad application. In order to determine the possible seismic risk and its aftereffects both during and after an earthquake, fragility curves have recently become crucial decision support tools (Billah, et al., 2014). The fragility curve may be used to determine if a bridge needs to be retrofitted or rebuilt, as well as to evaluate the safety of the structure. In this study, the methodology for fragility curve development was analytical fragility curve as stated in Billah, *et al* (2004) in Figure 1.

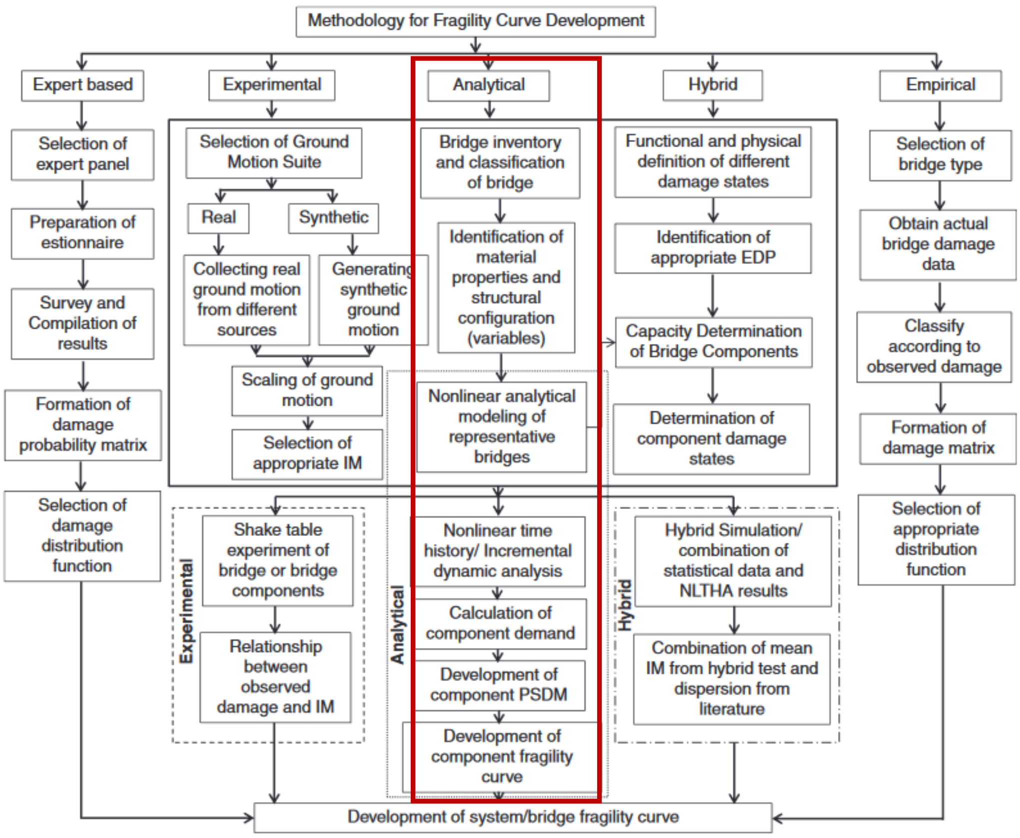


Figure 1 Methodology for developing seismic fragility curve

2. FRAGILITY FUNCTION

The probability value of a specific level of damage occurring in a structure is determined by calculating the cumulative value of the lognormal distribution, as expressed in Equation (1).

$$P[\text{Exceedence}|\text{IM}] = \Phi\left[\frac{1}{\beta tot}\, ln\,\frac{IM}{LSi}\right] \tag{1}$$

where IM is intensity measure of the earthquake; L_{Si} is the median value of IM to reach a level of damage; βtot is the uncertainty factor; Φ is Standard Normal CDF. The three main factors of uncertainty are the uncertainty definition of the level of damage, β_{ds}, the uncertainty of structural capacity, β_c and the uncertainty of seismic demand, βd. Uncertainty in the seismic fragility assessment framework involves two basic sources including irreducible aleatoric and inherent epistemic uncertainties. The aleatoric uncertainty is considered to capture the uncertainty in response due to variation in ground motion properties, whereas the epistemic uncertainty stems from the variation in material, geometric, and loading properties. In this study, β_{tot} was taken 0,78. as stated in another study by Simanjuntak,*et al*. (2022,2023)

3. METHODS

The multi-span concrete girder bridge type is the one examined in this study as it makes up a significant proportion of Indonesia's national bridge stock. Additionally, it is discovered that 30% of the bridges with multi-span structures in a typical bridge inventory may experience pier failure, which could cause serious economic consequences (Simon and Vigh (2016, 2017)). For this reason, assessment is crucial.

The study's primary emphasis was the continuous-integral Prestressed Concrete Box Girder bridge that is currently in place. Based on the information gathered, the structure's technical data: a) span length: 35-40 m (b) box girder width: 9 m (c) box girder height: 2,4 m (d) pier height: 7,6 m (e) diameter of pier: 2,7 m (f) fc': 29,05 MPa; fy: 400 MPa (g) tendon prestress PC-7-Wire, ASTM A-416, Grade 270 *low relaxation*. The pier detailing: (a) longitudinal rebar: 90 D32 (b) transverse rebar ratio: 0,009 (c) transverse rebar spacing: 100 mm as illustrated in Figure 2.

For analysis, each model is assessed based on the latest bridge loading regulations SNI 2833:2016 Bridge Design for Earthquake Load and 2017 Seismic Map. The structure analyzed is an existing bridge located in DKI Jakarta as a strong earthquake zone. Based on SNI 2833:2016 Article 5.6 Seismic Performance Category, there are 4 earthquake zones based on acceleration spectra with a period of 1 second (S_{D1}), namely earthquake zone 1 ($S_{D1} \leq 0.15$), earthquake zone 2 ($0.15 < S_{D1} \leq 0.30$) , earthquake zone 3 ($0.30 < S_{D1} \leq 0.50$) and earthquake zone ($S_{D1} > 0.50$). From Jakarta's spectral response, it can be seen that S_{D1} = 0.693, which means that Jakarta is in earthquake zone 4 (strong earthquake zone) (Figure 3).

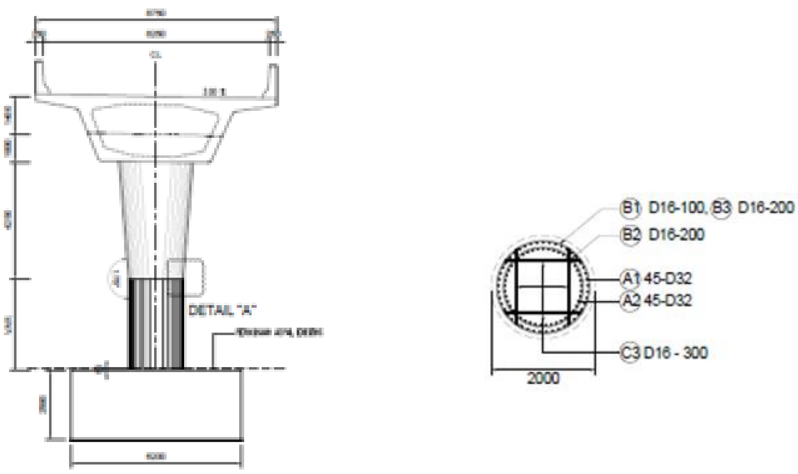
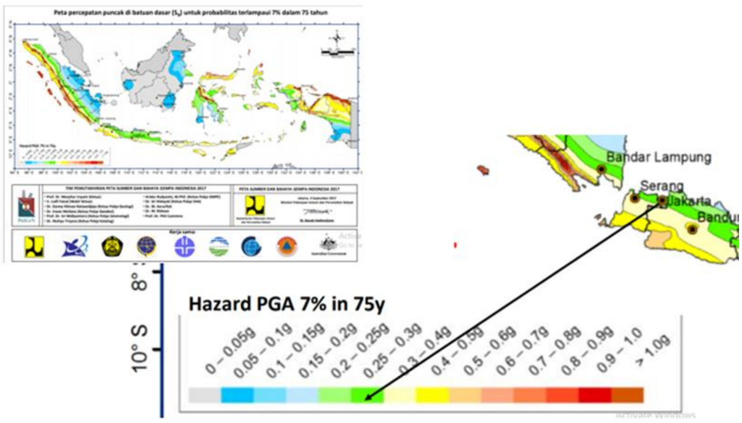
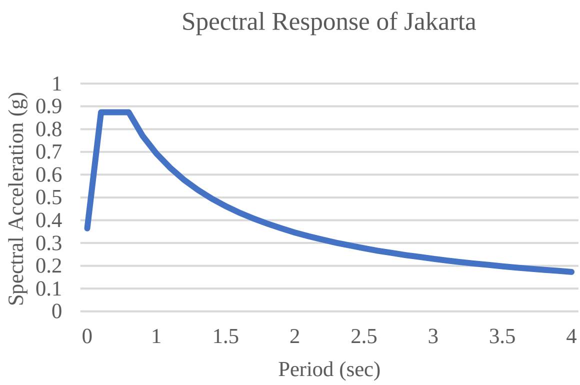


Figure 2 Typical pier reinforcement of existing bridge (Model 1-as built)





PGA (g)	0,272
Ss (g)	0,538
S1 (g)	0,223
Fa	1,625
Fv	3,108
F_{PGA}	1,338
$A_s = F_{PGA}$ PGA	0,364
SDS (g) = Fa Ss	0,874
SD1 (g) = Fv S1	0,693

Figure 3 Spectra response of Jakarta

The first step in an analytical process is establishing an appropriate numerical model of the bridge. In this study, geometry variations of pier as ERE was carried out to see the effect of these variations on the fragility. Parametric seismic evaluation. The models for variations in length (L_{span}) and column height (h_{pier}) are as shown in Table 1:

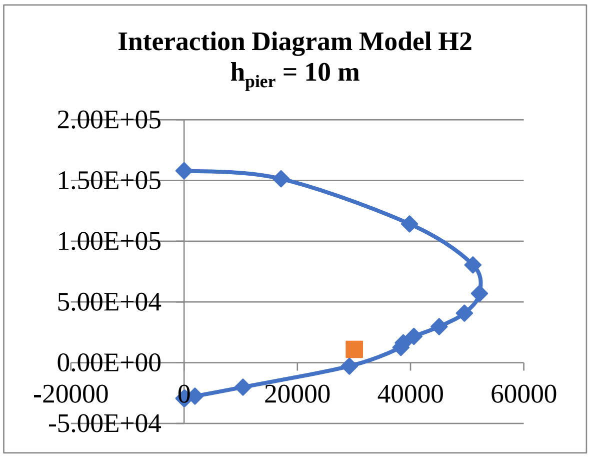
Table 1 Model of geometric variations

Model	Span Length (L_{span}) (m)	Pier Height (h_{pier}) (m)
H1	40	7,6
H2	40	10
H3	40	13

Design of reinforcement for variation models (Table 2) is carried out and checked of pier capacity, as shown by the interaction diagram (Figure 4). The over-capacity ratio for each bridge is in the range of 1,5.

Table 2 Details of the reinforcement model for variations in the height of pier

Model	L_{span} (m)	h_{pier} (m)	Pier Dimension ∅ (mm)	Longitudinal Bar	Transversal Bar
H1 (as built)	40	7,6	2700	90 D32	D16-100
H2	40	10	3000	112 D32	D16-100
H3	40	13	3500	135 D32	D16-100



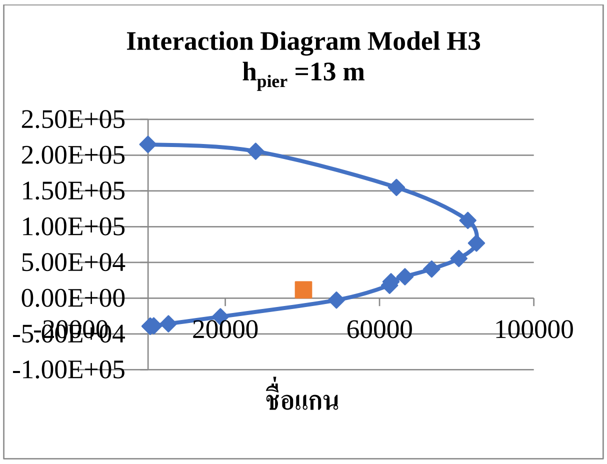


Figure 4 Pier cross-section interaction diagram pier height variation model

To simulate actual circumstances, every bridge is modeled using Midas Civil (Figure 5). The axial force acting on the pier, the cross-sectional dimensions, and the configuration of the reinforcement inserted in the pier cross section are entered to XTRACT to generate the moment-curvature curve. As can be seen in Figure 6, the stress-strain relationship in the steel material is described by the Bilinear with Strain Hardening model, whereas the inelastic behavior of the concrete material is characterized by the Mander Model (Mander et al., 1988). The calculation results of the curvature moment curve are shown in the following Figure 7 and Table 3.

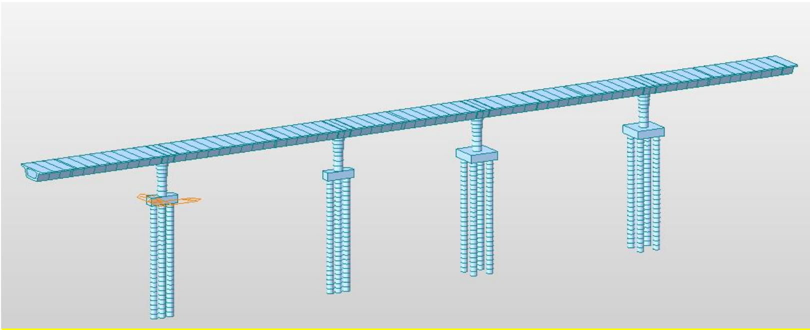


Figure 5 Bridge modeling in Midas Civil

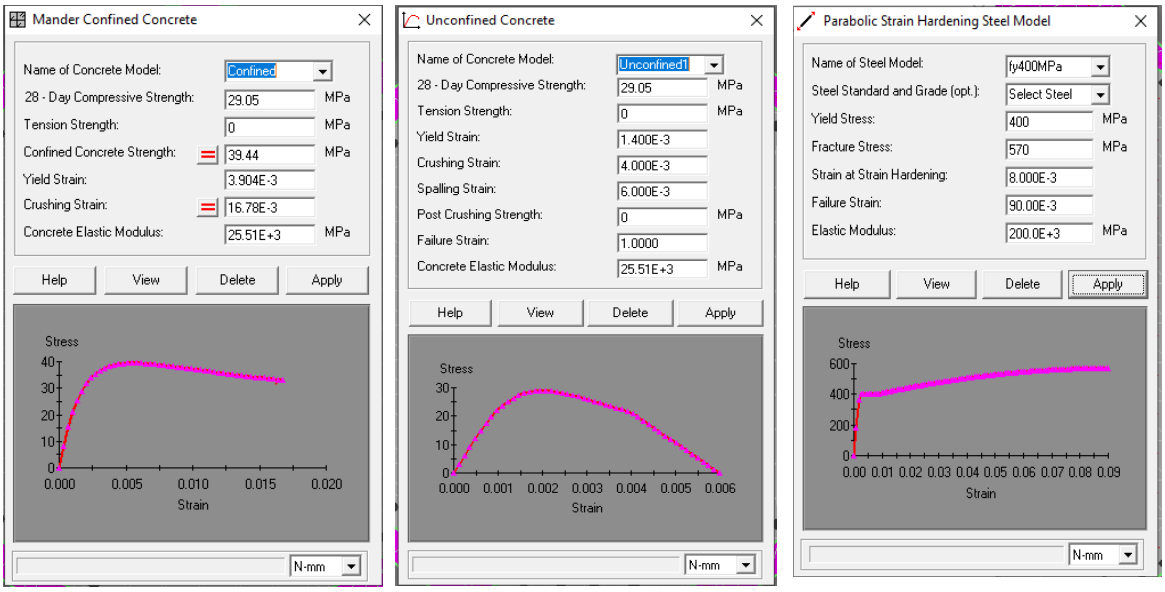
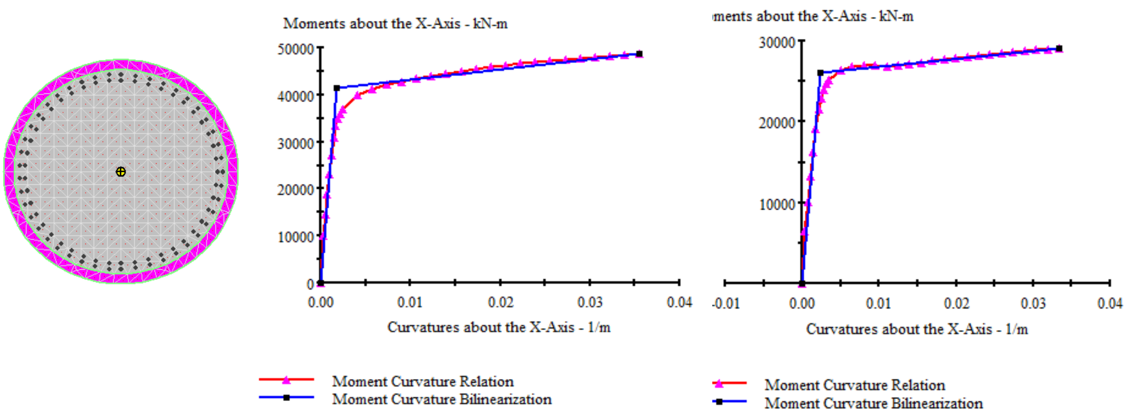


Figure 6 Non linear modeling



(a) Top (b) Bottom

Figure 7 Momen-curvature analysis in XTRACT (a) Top (b) Bottom

Table 3 Moment-curvature of pier cross section (longitudinal and transverse direction) (As built)

Pier			Momen (kN-m)	*Curvature* (1/m)
P88	Top	*First yield*	27520	0,0012
		Ultimate	49080	0,0353
	Bottom	*First yield*	19080	0,00176
		Ultimate	29110	0,0334
P89	Top	*First yield*	25650	0,001175
		Ultimate	47470	0,03641
	Bottom	*First yield*	19060	0,001851
		Ultimate	28330	0,03512
P90	Top	*First yield*	27730	0,001206
		Ultimate	49260	0,03512
	Bottom	*First yield*	19070	0,001745
		Ultimate	29200	0,03321
P91	Top	*First yield*	27070	0,001196
		Ultimate	48690	0,03543
	Bottom	*First yield*	19100	0,001782
		Ultimate	28910	0,0337

Next, NLTHA was used to analyze how the bridge structure responded to seismic loads. The maximum average value of the response value of the pier components' reaction value, assuming seven pairs of earthquakes were employed, is specified in AASHTO (2011). By utilizing recorded earthquake occurrences with particular criteria, such as magnitude (M), mean-source distance R and earthquake source mechanism, as displayed in Table 4, the de-aggregation technique for Jakarta selects appropriate ground motion. The amplitude scaling process was carried out to provide ground motion input that does not fall below the target response spectrum's spectrum acceleration.

Table 4 Specific ground motion

No	Earthquake Mechanism	Record GM	M	Epicentral Distance (R) (km)	Data Source
1	Subduction Interface (Megathrust)	Chile (Curico)	8,8	178	USGS/CESMD
2		Tohoku (FKS006)	9,0	170	USGS/K-NET
3		Chi Chi (TAP075)	7,62	160,21	PEER
4		Tokachi-Oki (HKD094)	8,3	156,5	USGS/K-NET
5	Deep Subduction Interslab (Benioff)	Miyagi Oki (MYGH08)	7,0	127,9	USGS/K-NET
6	Shallow Crustal Fault & Background	Livermore (STP)	5,8	54	PEER
7		Landers (SER)	7,28	73,2	PEER

Non-linear time history analysis is employed, and it is thereafter enhanced gradually (Incremental Dynamic Analysis/IDA). In order to achieve damage distribution for the several degrees of earthquake intensity–Slight Damage, Moderate Damage, Extensive Damage and Complete Damage–the seismic force is gradually raised (Vamvatsikos, 2002).

In fragility assessment, one crucial step is to estimate the degree of seismic damage, either quantitatively or qualitatively. According to research by Jain A., et al., 2020, the damage index values for the piers are calculated using drift (%) limitations and a damage index 0.9 indicates that the structure has completely collapse. Various demand parameters have been researched to measure the damage state of bridge. However, in this research, the drift computed from the steel strain limits and concrete strains is used to determine performance levels to evaluate the outcomes of non-linear seismic analysis based on NCHRP 440.

Table 5 Bridge performance / design parameters based on NCHRP 440 (2013)

Level	Description	Steel Strain	Concrete Strain	Drift
I	Elastic-Fully Operational	<0,005	<0,0032	$\varphi = \frac{\varepsilon_c}{kd} = \frac{\varepsilon_s}{d\,(1-k)} = \frac{\varepsilon_c + \varepsilon_s}{d}$ $\theta = \varphi \times Lp$ $drift = \theta \times h_{pier}$
II	Operational	0,005	0,0032	
III	Life Safety	0,019	0,01	
IV	Near Collapse	0,048	0,027	
V	Collapse	0,063	0,036	

In NCHRP Sythesis 440, performance-based seismic design is explained, which is a design concept in which a performance level is determined in the structure due to earthquake loading. The behavior of a structure is measured by the level of damage that can be related to the functionality of the bridge as seen in Figure 8 and Table 6.

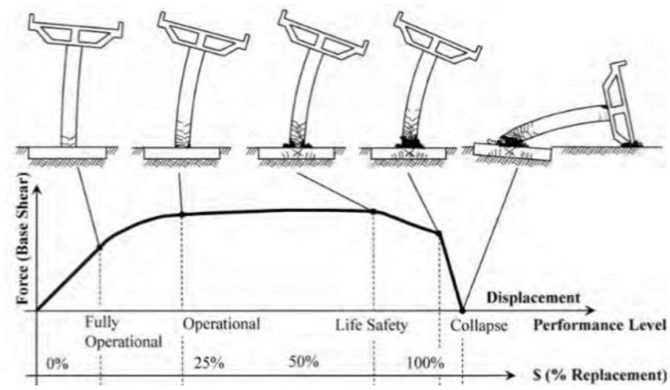


Figure 8 Visualisation bridge damage and performance assessment (NCHRP 440)

Table 6 Bridge damage and performance assessment (NCHRP 440)

Damage Level	Damage Classification	Damage Description
I	No	Onset of hairline cracks
II	Minor	Crack widening; Theoretical first yield of longitudinal reinforcement
III	Moderate	Beginning of inelastic deformation; Onset of cover concrete spalling; Development of diagonal cracks
Damage Level	**Damage Classification**	**Damage Description**
IV	Major	Formation of very wide cracks; Extended concrete spalling
V	Collapse	Buckling of main reinforcement; Rupture of transverse reinforcement; Crushing

4. RESULTS

From the NLTHA results, the drift value of each maximum displacement value on the pier was observed. From the maximum drift value, the level of damage (damage state) experienced by the bridge is identified and the performance level of the structure due to the acting earthquake load is determined. The results of NLTHA with ground motion input that is compatible with the target response spectrum with various values of $As = F_{PGA}$ X PGA are shown in Table 7. The damage limitations referring to NCHRP 440 are shown in Table 8. The plastification in bridge column (collapse) can be seen in Figure 9.

Table 7 Various target response spectrum scenarios and identification of performance levels using Incremental Dynamic Analysis (Model H1-as built)

$A_S = F_{PGA}$ x PGA (g)	PGA (g)	Average Disp (meter)	Damage State	Performance level
0,10	0,07	0,0308	Slight Damage	<Operational
0,20	0,15	0,0665	Moderate Damage	Operational-LS
0,30	0,22	0,0977	Moderate Damage	Operational-LS
0,40	**0,27**	**0,1238**	**Moderate Damage**	**Operational-LS**
0,50	0,37	0,1538	Moderate Damage	Operational-LS
0,60	0,45	0,1927	Extensive Damage	LS-NC
0,70	0,52	0,2265	Extensive Damage	LS-NC
0,80	0,60	0,2434	Extensive Damage	LS-NC
0,90	0,67	0,2783	Extensive Damage	LS-NC
1,00	0,75	0,3145	Extensive Damage	LS-NC
1,10	0,82	0,3357	Extensive Damage	LS-NC
1,20	0,90	0,3531	Extensive Damage	LS-NC
1,30	0,97	0,3936	Extensive Damage	LS-NC
1,40	1,05	0,4190	Extensive Damage	LS-NC
1,50	1,12	0,4462	Complete Damage	NC-Collapse

Table 8 Damage state (Model H1-as built)

Description	Curvature	Rotation	Drift (m)
Operational	0,00247	0,0067	0,0508
Life Safety	0,00773	0,0209	0,1587
Near Collapse	0,02088	0,0564	0,4284
Collapse	0,02784	0,0752	0,5713

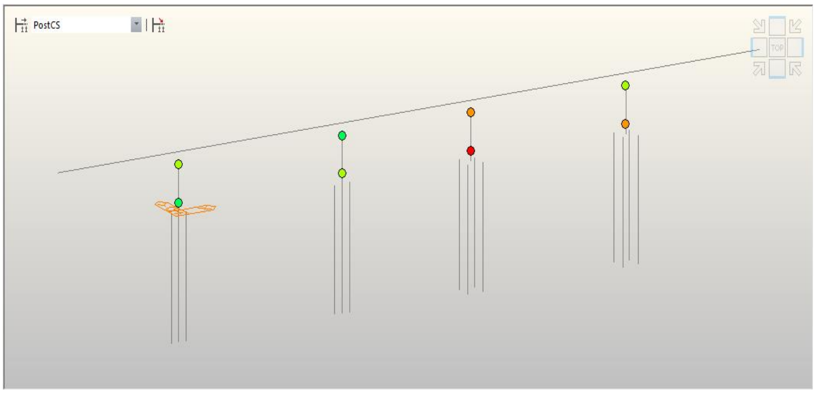


Figure 9 Plastification in Midas Civil- complete damage (as built)

The same procedure is carried out on other geometric variation models and the values obtained are As = F_{PGA} x PGA values for each damage condition for a probability of exceeding >50% for each bridge variation model can be seen in Table 9.

Table 9 Recapitulation of the value of As = F¬ x PGA for each damage condition for a probability of exceeding >50% for each bridge variation model

Model	h_{pier} (m)	L_{span} (m)	Damage State			
			Slight	Moderate	Extensive	Complete
Variasi h_{pier}						
Model H1 (as built)	7,6	40	0,20	0,50	0,92	**1,5**
Model H2	10	40	0,20	0,44	0,90	**1,3**
Model H3	13	40	0,20	0,44	0,84	**1,2**

The change of pier collapse rises with pier height, as seen by Table 9 and the derived fragility curve (Figure 10), which shows the cumulative distribution function (CDF) based on Equation 1. As the height of the pier increases it is more likely to be damaged in an earthquake event. Taller piers were more flexible and had longer vibration periods, making them more susceptible to seismic forces. However, the spectral area must also be taken into account. Pier height has a major impact on the fragility curve; taller piers are more susceptible to seismic activity, as demonstrated by the rate of change in IM which is significant in cases of extensive and complete damage. $IM_{collapse}$ for h_{pier} = 13,2 m is approximately 1,5 g while $IM_{collapse}$ for h_{pier} =7 m is approximately 1,2 g, for chance of exceedance >50% (collapse/complete damage). It can be inferred that an increase of in h_{pier} of two times causes an $IM_{collapse}$ difference up to 0,3-0,4 g. Taller piers will have a reduced ductility capacity because of the impact of higher elastic deformation on overall displacement, as indicated by the decreasing ratio of plastic hinge length to overall pier height with rising pier height (NCHRP 440). The findings of this study's generalization of the fragility curve are utilized to predict the likelihood level of bridge damage in the same class, which includes the pier, deck, and pier to deck connection types, as well as an over capacity ratio of 1.5.

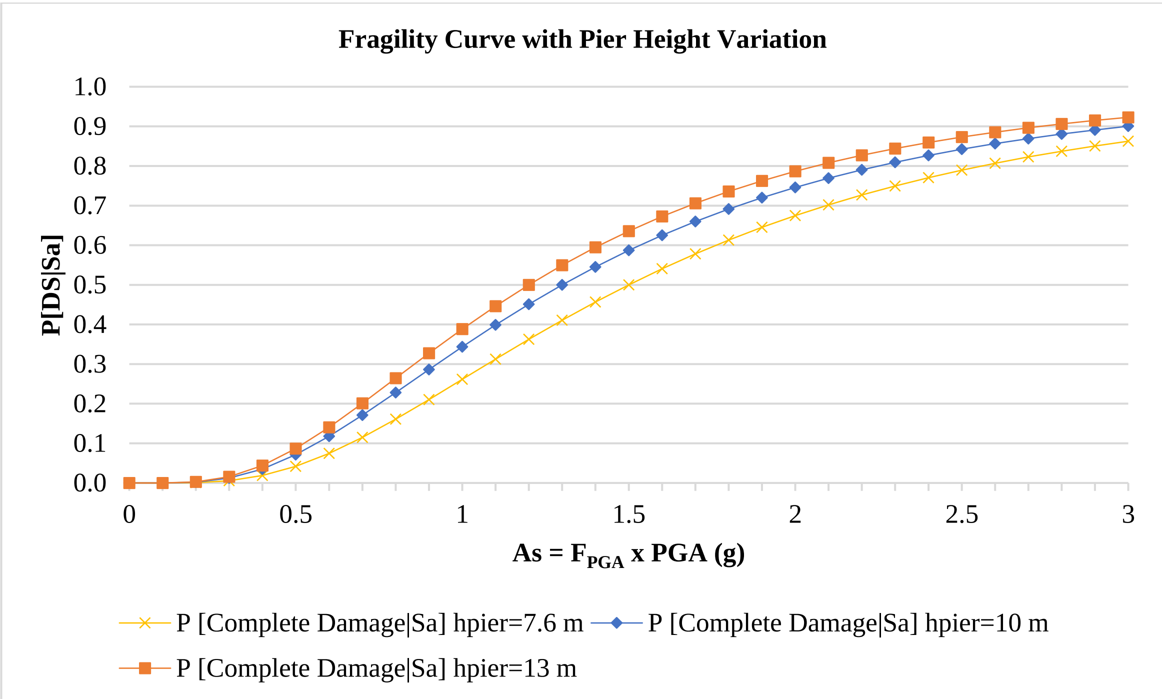


Figure 10 Fragility curve with variation pier height

5. CONCLUSIONS

This paper presents an overview of the seismic fragility analysis conducted on existing bridges across varied pier height. It was found that higher pier is more susceptible to seismicity as seen from the rate of change in IM which is significant. The results also show that the fragility curve of the bridge with higher pier is steeper, indicating that it was more vulnerable. This paper has clearly revealed that recently pier properties as Earthquake Resisting Element has significant influenced bridge vulnerabilities. It can be inferred that an increase of in h_{pier} of two times causes an IMcollapse difference up to 0,3-0,4 g. By employing this simplification methodology, it becomes feasible to approximate the probable of structural damage for a stock of bridges in the same class, namely the pier, deck, pier to deck connection types and also over capacity ratio of 1.5.

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Business Continuity Plan (BCP) for urban expressway in preparation for a major earthquake

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ABSTRACT

The Hanshin Expressway plays an important social role in contributing to the livelihood and economic development of the Kansai region. So, it is essential that the Hanshin Expressway should be accessible to emergency vehicles in case of a major earthquake.

With this background, the Hanshin Expressway has formulated the Business Continuity Plan (BCP), a wide and cross-sectional action plan, as a soft measure in addition to hard measures such as earthquake resistance measures. This paper summarizes the role of the BCP and related initiatives. The importance of the BCP is that it prevents confusion on-site and helps businesses recover quickly by clarifying in advance the priority actions to be taken and the division of roles in the event of an emergency.

In addition, it is important to continuously review the contents of the BCP through drills and other means to examine and improve issues that emerge.

Keywords: Business Continuity Plan (BCP), Earthquake, Emergency Action, Countermeasure for the disaster, Emergency drills

1. INTRODUCTION

Japan is located in one of the most quake-prone areas in the world, where four tectonic plates collide, creating approximately 2,000 active faults. According to the Japan Institute of Country-ology and Engineering (JICE), 17.9% or 259 of earthquakes measuring 6.0 or higher on the Richter scale in the world between 2011 and 2020 occurred near Japan, highlighting the critical need for Japan to formulate national measures (General Incorporated Foundation Japan Institute of Country-ology and Engineering,2024).

As shown in Figure 1, the Hanshin Expressway extends 258.1 km across the urban areas of Osaka and Hyogo prefectures in the middle of the Japanese archipelago. Running through urban areas, the expressway plays an important social role in contributing to the quality of life and economic development in the Kansai economic region. For this reason, the entire Hanshin Expressway has been designated by local governments as an emergency transport road that must ensure the passage of emergency vehicles to enable relief operations, such as evacuation, rescue, and supply provisions, immediately after a disaster, such as a major earthquake, occurs.

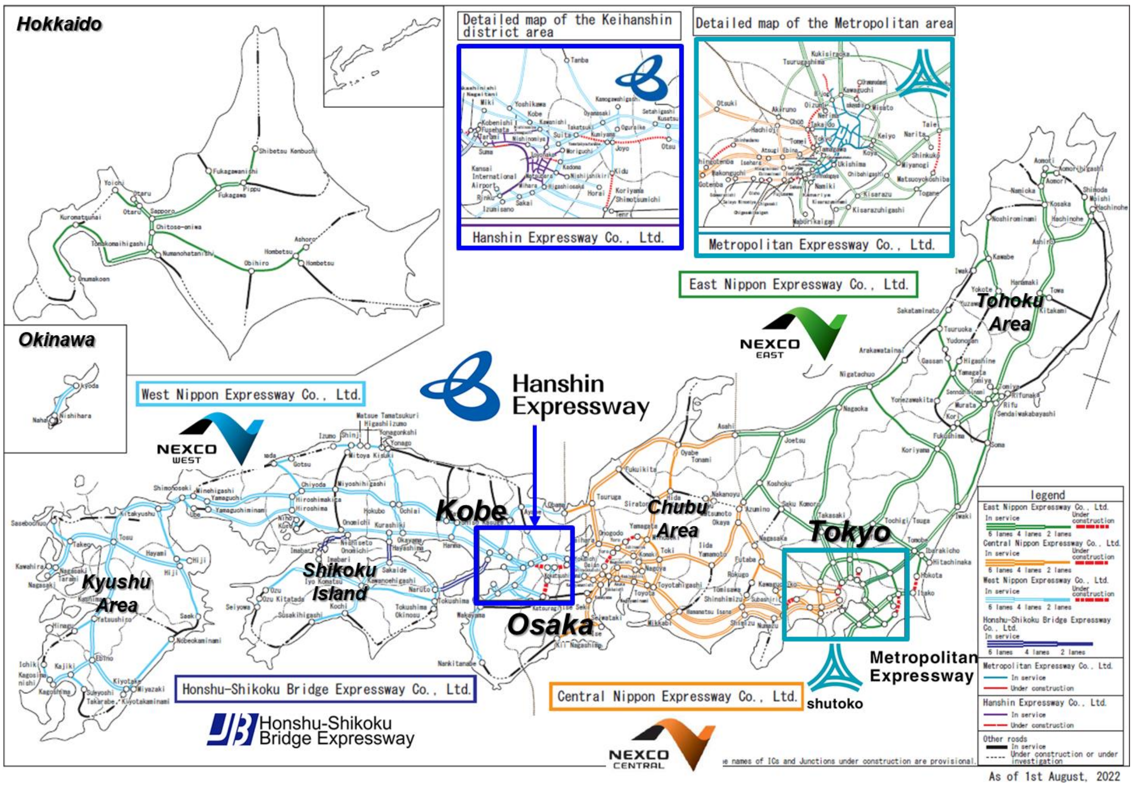

Figure 1 Location of the Hanshin Expressway.

Against this background, Hanshin Expressway Co., Ltd. has formulated and implemented a company-wide, cross-sectional business continuity plan (BCP). This paper summarizes the role of the BCP in preparing for a major earthquake, as well as emergency drills to continuously verify the effectiveness of the BCP. In the following sections, we first introduce the concept of the BCP, overview the Hanshin Expressway BCP, exemplify the emergency drills conducted to ensure continuous review of the BCP, and finally reaffirm the significance of the BCP for the future.

2. The significance of formulating a BCP and an overview of the Hanshin Expressway BCP

2.1 The concept of a BCP

A business continuity plan (BCP) specifies the activities to be performed by the company during normal times, as well as the ways and means for continuing operations in an emergency, to minimize damage to business assets and enable the continuation or early recovery of key operations in the event of a natural disaster, major fire, terrorist attacks, or other emergencies (Small and Medium Enterprise Agency,2024). Formulating a BCP in advance can improve the company's emergency capabilities and minimize damage caused by a disaster.

Figure 2 shows the degree of business continuity over time with and without a BCP in place. The two advantages to be brought by formulating a BCP in advance are as follows: (1) By taking damage prevention measures through a BCP, you can continue your key operations at a level above acceptable limits, and (2) By planning in advance what to do after a disaster through a BCP, you can restore your operations within an acceptable time.

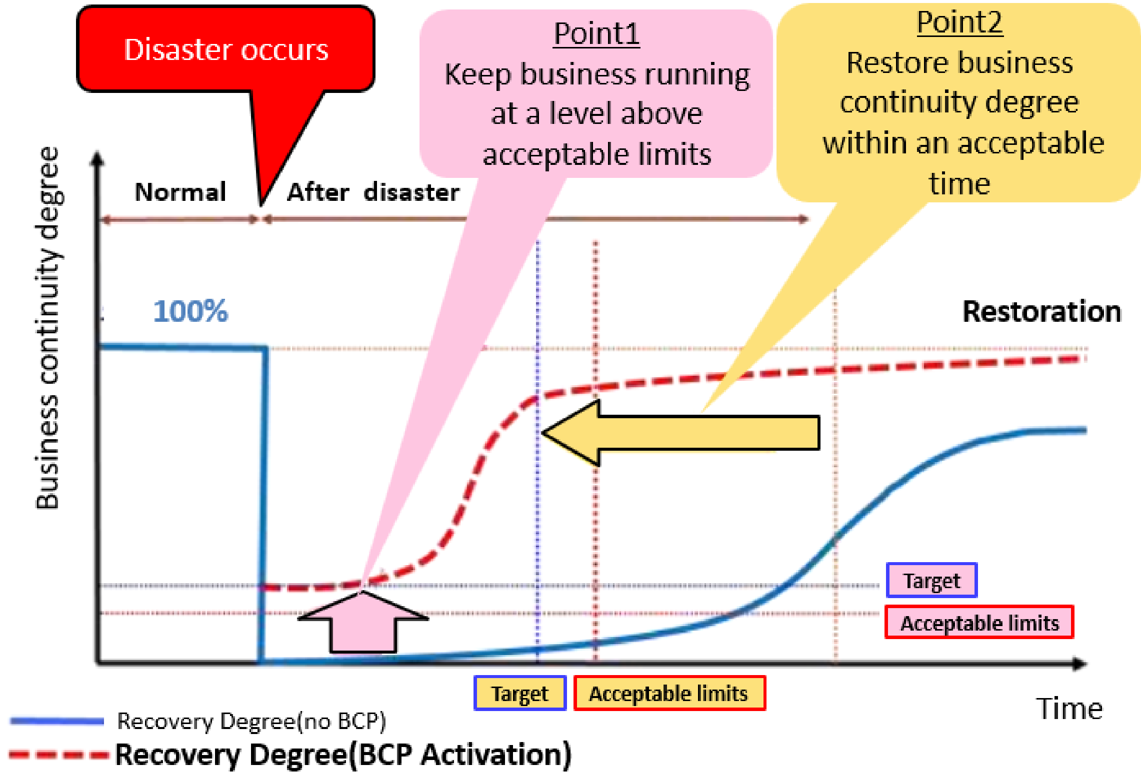

Figure 2 Recovery with and without a BCP (Study Group on Measures to Promote the Formulation of Business Continuity Plans from Cabinet Office,2009).

Formulation of the Hanshin Expressway BCP was triggered by the Great Hanshin-Awaji Earthquake, measuring 7.3 on the Richter scale, which occurred in 1995. This massive earthquake caused major damage to the Hanshin Expressway. Learning the lessons from this earthquake, Hanshin Expressway Co., Ltd. has decided to formulate a BCP as a software measure, in addition to hardware measures for road structures, such as aseismic reinforcement for bridges and flooding measures against tsunami.

Figure 3 Examples of Damage to the Hanshin Expressway Caused by the Great Hanshin-Awaji Earthquake in 1995.

2.2 Overview and behavioral objectives of the Hanshin Expressway BCP

The Hanshin Expressway BCP has been formulated on the premise that operations would not be interrupted even in the event of a disaster or other damage and that even if the operations are interrupted, they would be restored as quickly as possible. Based on this policy, the BCP specifies how to respond and how to operate organizations in the event of a disaster, including preparation of resources, such as people, materials, and information, in advance, so that critical operations can be performed and continued, while other interrupted key operations can be restored within an acceptable period of time.

Since expressways are social capital that provides services to the public, we prioritize the following three principles from the perspective of urgency: (1) Ensuring safety, including human lives, and preventing secondary disasters, (2) Contributing to disaster relief and recovery by securing emergency transportation road functions in the event of a disaster, and (3) Contributing to the recovery of people's lives and the economy through the early resumption of toll expressway operations. To realize the above, the Hanshin Expressway BCP focuses on securing the necessary personnel and collecting, organizing, and providing appropriate information. In addition, to ensure easy and quick understanding, the contents of the BCP are divided into two major parts. The first part specifies emergency prevention (advanced measures), a summary of actions that should be prepared in advance, to enable continuous or restored operations of emergency handling and general importance within a certain period of time even if damage is caused by a disaster. The second part specifies the post-disaster actions, a summary of actions that should be taken after a disaster occurs.

The above post-disaster actions further specify the behavioral objectives for each period in a chronological framework, such as within 1 hour, 3 hours, 12 hours, 24 hours, 3 days, and 7 days after a disaster occurs. By organizing the action plans as above, the Hanshin Expressway BCP enables its employees to quickly determine the priority actions to be taken after a disaster occurs without confusion. Table 1 shows an overview of the chronological behavioral objectives of the Hanshin Expressway BCP.

Table 1 Top-Priority Chronological Behavioral Objectives in the Post-Disaster Actions.

Restoration Target Time	Matters to Begin	Concrete Action		
		Establishment of Implementation System	**Saving Lives, Securing Emergency Transportation**	**Others**
Within 1 hour	Distribute information (First Report)	• Assemble BCP staff (if disaster occurs outside of working hours), Assemble other employees • Emergency inspection of buildings etc.	• Gather Information	• Providing information to relevant organizations (first report) • Establishing a disaster control headquarters and front-line outposts
Within 3 hours	Understand the situation	• Checking employee attendance • Establish first action plan	• Respond to victims • Understand situation of our road network, toll booths, system, places under construction	• Press release • Providing information to customers
Within 12 hours	Removal of obstacles on the road		• Remove evacuated vehicles, secure roadways • Remove obstacles and prevent secondary disaster	• Under-the-road situation assessment • Starting administrative work to enable the passage of emergency transport vehicles
Within 24 hours	Secure minimum emergency transportation		• Development of restoration plan and implementation of construction • Resume emergency transportation paths after confirming safety	
Within 3 days	Formulation of a full restoration plan	• Implementing shiftwork for emergency personnel	• Conducting a full restoration inspection and formulating a full restoration plan	• Conducting detailed inspections of company buildings • Collecting information related to disaster recovery costs
Within 7 days	Implementation of full restoration work		• Discussing full restoration work with relevant organizations and starting the work	• Conducting the procedures related to the applications for regulatory approval of restoration projects

Our BCP further breaks down each item and specifies detailed actions required.

2.3 Hanshin Expressway Emergency Organizations in the event of an earthquake

The Hanshin Expressway BCP describes not only the specific actions listed above but also the emergency organizations to be adopted. Hanshin Expressway Co., Ltd. adopts an emergency system that differs from the one in normal times, assigning all relevant employees to any one of the task force teams. The post-disaster action plan mentioned above classifies and organizes the specific actions to be taken by each task force team, enabling easy understanding of the actions to be taken by the team to which each person belongs.

Figure 4 outlines the emergency organizations. The overall functions are mainly divided into a disaster control headquarters responsible for general and rearguard support functions and front-line outposts responsible for fieldwork functions, with each organization sharing different responsibilities. The disaster control headquarters compiles information on damage and other matters and coordinates with external parties, while the front-line outposts carry out actions focused on the site, such as grasping the on-site situation and arranging emergency restoration work there.

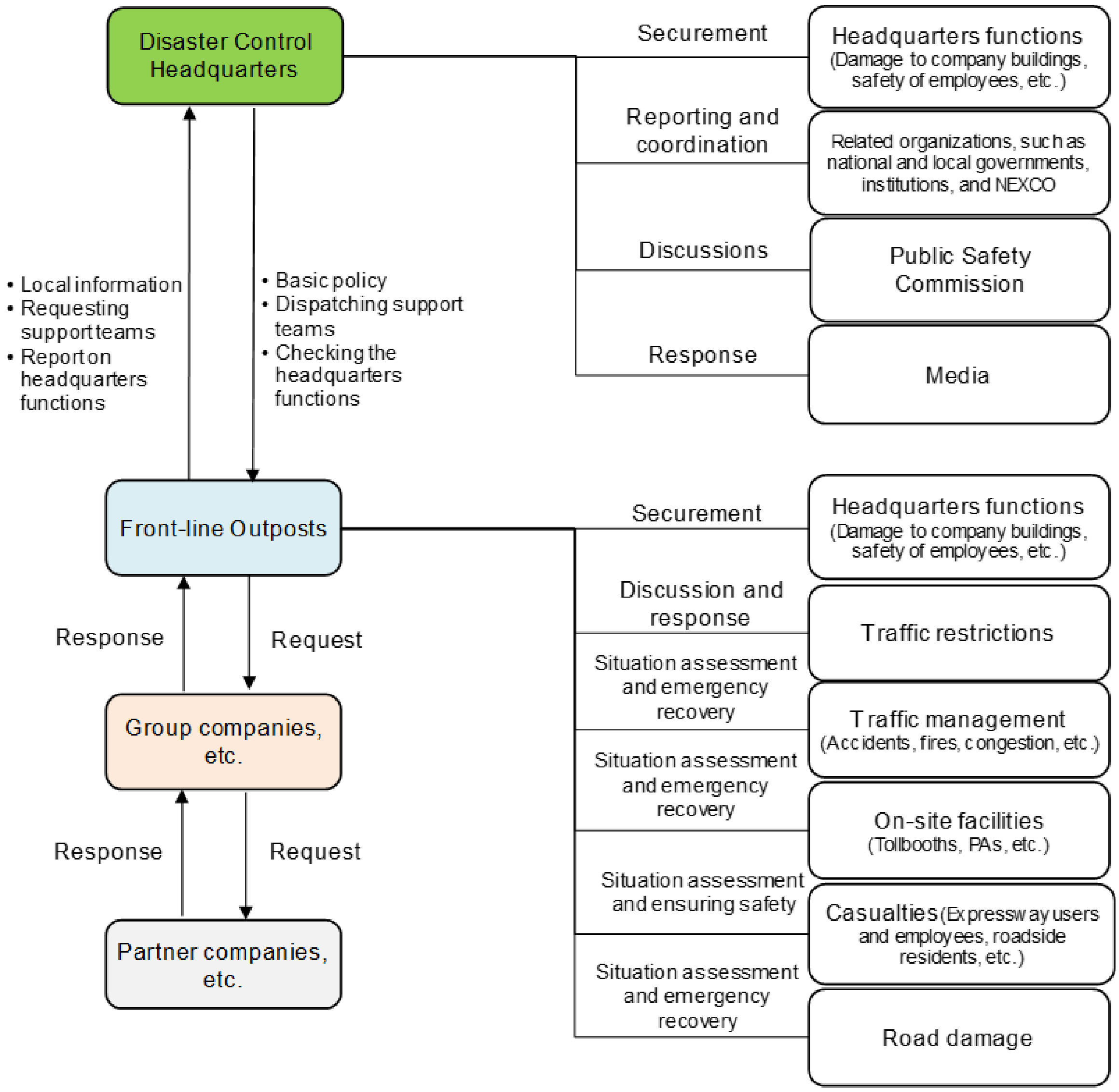

Figure 4 Emergency Organizations and Roles of the Disaster Control Headquarters and the Front-Line Outposts.

In addition, the disaster control headquarters and the front-line outposts each have multiple task force teams, of which responsible actions specified by the BCP to be taken by each task force team. For example, the overall control team is responsible for overall coordination of the disaster control headquarters and supervision of each task force team, the general affairs team distributes and manages emergency equipment, the conservation traffic team summarizes the results of inspections of expressways and facilities, etc.

3. Continuous updating of BCP

3.1 Comprehensive emergency drills to continuously review BCP

A BCP essentially requires continuous review of its contents by verifying its effectiveness, rather than once formulating it and then leaving it untouched. The Hanshin Expressway BCP involves continuous review of its contents by using the plan-do-check-act (PDCA) cycle to examine and improve any problems that emerged through drills and practices and update the plan. To check the feasibility of its BCP, Hanshin Expressway Co., Ltd. conducts emergency drills, reviews its immediate response efficiency, and practices its continued operation, in the event of a disaster. The following section overviews the two emergency drills conducted by the Hanshin Expressway Group.

The first drill is a comprehensive emergency drill. This large-scale annual drill is conducted by Hanshin Expressway Group companies. Any problems that emerged as a result of the drill are continuously examined and improved. The drill assuming a major earthquake and subsequent tsunami requires the participants to play their assigned roles for a whole day. Based on expected damage to the expressway, each task force team examines what actions it should take and when based on the BCP and starts actions in anticipation of a disaster.

In addition to classroom lessons, they also conduct practical training that simulates actual work to be carried out on-site. Such practical emergency drills include the inspection of damage to road structures using electronic systems, communication with external related organizations, and bump repairs on expressways in cooperation with the Self-Defense Forces. Conducting such practical drills can facilitate and expedite a range of work to be done in the event of a real disaster. After conducting the comprehensive emergency drill, all relevant parties come together to discuss any problems discovered during the drill, areas for further improvement, and any necessary update of the BCP. Through these practices, the Hanshin Expressway BCP has been repeatedly improved.

Figure 5 Comprehensive Emergency Drill.

3.2 Road clearance training simulating stalled vehicles on site

The second drill is road clearance training conducted in 2024. This on-site training was conducted to secure the passage of emergency vehicles stipulated in the BCP when a major earthquake blocked the main expressway route.

Figure 5 shows the assumed road situation. A Nankai Trough earthquake created an uneven joint on the elevated expressway road, causing vehicle (1) traveling on the main route to suddenly brake and overturn on the centerline. Subsequently, the six vehicles following the vehicle (1) stopped behind there. Then, the drivers of six of these seven vehicles evacuated via the fire escape. The objectives of this emergency drill are to secure at least one lane by removing these stalled vehicles and repair the uneven road surfaces to enable emergency vehicles to pass.

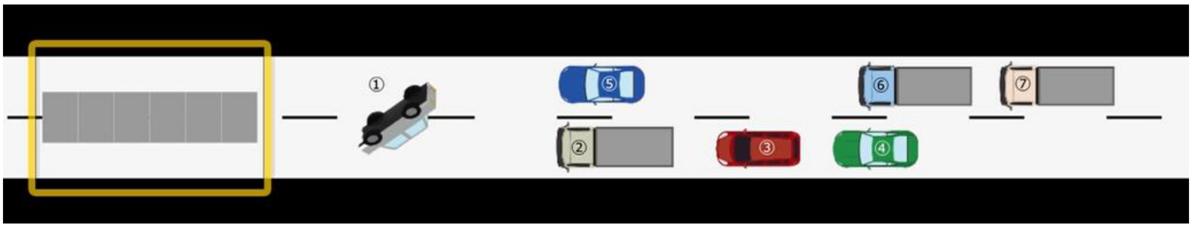

Figure 5 Map of Assumed Road Situation (The yellow-framed box shows the area of uneven surfaces on the main route.).

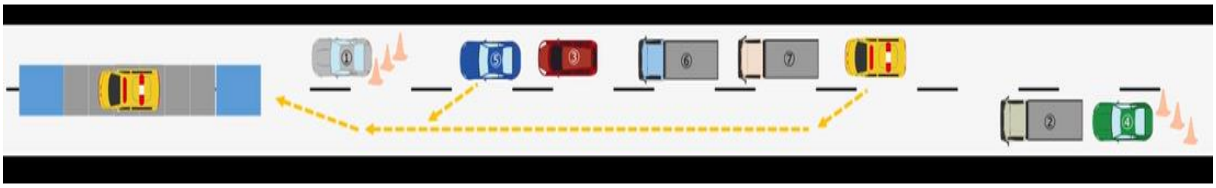

Figure 6 Map of Cleared Road Situation.

First, the traffic patrol unit shall conduct a special patrol to assess and report to the front-line outpost the status of overturned vehicles, the types and number of stalled vehicles, and the status of bumps. The initial emergency actions stipulated in the BCP require us to formulate a special patrol plan, dispatch the patrol unit to assess the road situation within three hours after the occurrence of a disaster, and report the damage situation to the front-line outposts and related sections, if any is found.

After receiving the inspection report from the patrol unit, the front-line outpost shall order the road clearance unit and the bump repair unit to hurry to the site. The BCP stipulates that the front-line outpost shall take emergency measures, such as removing obstacles and preventing secondary disasters, within 12 hours as a general rule. When it is necessary to move aside stalled vehicles to secure the passage of emergency vehicles during a large-scale disaster, the road administrator (in this case, Hanshin Expressway Co., Ltd.) shall be authorized to move aside the vehicles after coordinating with relevant authorities and designating the relevant road section under the provisions of the Disaster Countermeasure Basic Act. After receiving designation under the Disaster Countermeasure Basic Act, our road clearance unit shall arrive at the site and make a record of and photograph the road situation there before clearance, such as whether overturned and stalled vehicles need to be moved aside to create the passage of emergency vehicles.

Then, the road clearance unit shall move aside the stalled vehicles. Vehicles left with their doors locked shall be moved aside by using a GOJAK, a vehicle lifting and carrying dolly, or by breaking the windows to release their handbrake so that they can be towed backwards by a traffic patrol car. Overturned vehicles (1) shall be pulled by a traffic patrol wrecker and moved aside by using a GOJAK, a vehicle lifting and carrying dolly. Once the passage for emergency vehicles is secured, the road clearance unit shall make a record of and photograph the road situation there after clearance and report task completion to the front-line outpost.

Figure 7 Moving out Stalled Vehicles using a GOJAK, a vehicle lifting and carrying dolly or a wrecker.

The bump repair unit shall investigate the on-site situation and install bridging boards over bumps according to the instructions from the supervisor. Once installation is completed, the bump repair unit shall try to pass its vehicle over the bridging boards to confirm their safety.

Figure 8 Installation of Bridging Boards Over Bump to Enable Smooth Vehicle Passage.

Through the above procedures, the passage of emergency vehicles on the main route of the expressway shall be secured. The training provided us with the first opportunity to simultaneously move aside overturned and stalled vehicles and repair road surface bumps, successfully completing the tasks without any major problems. By coordinating and conducting multiple tasks in a drill in this way, we can verify and improve the effectiveness of the specific tasks described in the BCP.

4. RESULTS

Formulating a BCP is important for an expressway company, not only to interrupt its operation even in the event of a disaster but also to restore its key operations as quickly as possible even if they are interrupted. In addition, continuously reviewing the BCP by verifying its effectiveness through the above drills and examining and resolving emerging problems is also important.

After finishing each drill, Hanshin Expressway Co., Ltd. holds a meeting to discuss how to better respond in the event of a disaster and how to update its BCP, including new measures to be taken. For example, through drills, a discovery of a problem on redundancy of the communications environment between each outpost has led the company to hold a discussion among relevant sections to introduce a new communications environment. In addition, another discovery of a problem of insufficient system functions to summarize important information, such as structural damage and human casualties after an earthquake, has led the company to expand its system functionalities. Moreover, by having each task force team conduct training based on chronological order assuming the occurrence of a disaster, the company has improved the details of the actions to be taken by each task force team as described in the BCP.

No one knows when a disaster will occur. Therefore, advanced preparations, such as formulating a BCP and conducting drills to continuously review its contents, are extremely important.

5. CONCLUSIONS

The Headquarters for Earthquake Research Promotion in Japan has assessed that there is a 70% to 80% probability of a magnitude 8 to 9 earthquake occurring in the Nankai Trough in Japan within the next 30 years (Headquarters for Earthquake Research Promotion,2024). To prepare for earthquakes, not limited to the Nankai Trough earthquake, Hanshin Expressway Co., Ltd. continues to review its various action plans, including its BCP. In particular, as the Nankai Trough earthquake is expected to accompany a subsequent tsunami, how to efficiently and effectively conduct initial response activities, such as guiding expressway users to safety, has become increasingly important.

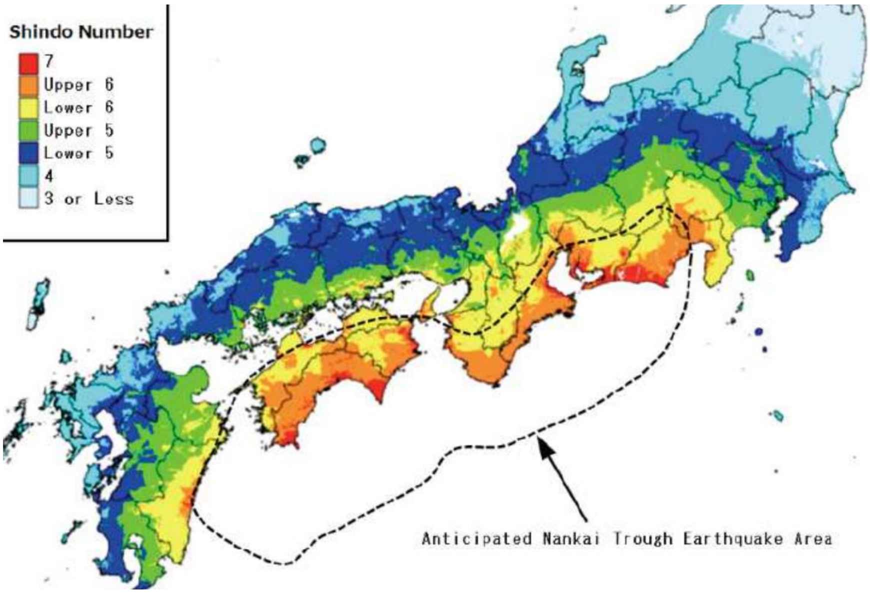

Figure 9 Map of Maximum Seismic Intensity Distribution for Nankai Trough earthquakes (Japan Meteorological Agency,2022).

The Hanshin Expressway BCP specifies the process of how to continue key operations while controlling its own damage potentially caused by a disaster. In the event of a disaster, resources such as available staff and information are limited. The Hanshin Expressway BCP is, in principle, formulated to automatically operate the plan even in such situations. Therefore, how each one of us deeply understands the details is also important. The company will strive to further improve its emergency capabilities by continuously reviewing the BCP and further increasing the proficiency and action levels of our employees.

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ENVIRONMENTAL AND ECONOMIC ANALYSIS OF HOT-MIX ASPHALT AND WARM-MIX ASPHALT PAVEMENT CONSTRUCTION: A CASE STUDY IN THAILAND

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ABSTRACT

Pavement construction plays a critical role in the development and upkeep of transportation infrastructure, ensuring safe and efficient travel for individuals and goods. However, these essential activities are not without their environmental consequences, particularly in regions like Thailand, where the issue of emissions has become a growing concern. Asphalt constitutes over 90% of paved roads in Thailand, with hot mix technology being the predominant method for asphalt mixture production, demanding substantial energy and fuel usage, especially for aggregate drying and asphalt heating processes, necessitating temperatures exceeding 160°C throughout production and construction. In this study, a cradle-to-gate life cycle assessment was conducted to evaluate environmental impacts, focusing on energy consumption and CO_2 emissions. The base cases represented conventional Hot Mix Asphalt (HMA), which was widely used in Thailand. The 14 alternative cases include reclaimed asphalt pavement (RAP) utilization and three types of warm mix asphalt (WMA) technologies: Sasobit; Evotherm; and Advera. The results obtained from the base cases establish the threshold, as the study aims to identify the optimal solution for reducing CO_2 emissions in pavement construction projects. Subsequently, the reduction in CO_2 emissions is treated as a benefit in the cost-effectiveness analysis, allowing for an evaluation of the most suitable alternative in terms of both environmental and economic considerations. The results suggest that, for conventional HMA, CO_2 emissions are primarily released from two main processes: raw material production and asphalt mixture production. In asphalt mixture production, more than 60% of the CO_2 comes from heating aggregates followed by 24% from water vaporization. Among the three types of warm mix additives, Evotherm performs best in terms of emissions reduction in the asphalt mixture production process. However, to make it economically successful, WMA needs to be incorporated with RAP materials.

Keywords: Reclaimed asphalt pavement, Warm mix asphalt, Life cycle assessment, Cost-effectiveness analysis

1. INTRODUCTION

Pavement construction plays a critical role in the development and upkeep of transportation infrastructure, ensuring safe and efficient travel for individuals and goods. However, these essential activities are not without their environmental consequences, particularly in regions like Thailand, where the issue of emissions has become a growing concern.

In recent years, Thailand has recognized the severe impacts of climate change and the significance of holding the increase in global average temperature to well below 2 °C and pursuing efforts to limit the increase to 1.5 °C under the Paris Agreement. Achieving these temperature goals requires significant emission reductions globally, as the magnitude of global warming is closely linked to cumulative greenhouse gas emissions.

According to ClimateWatch, it is shown that Thailand emitted 451.42 $MtCO_2eq$ of GHG in 2020 representing 0.95% of global emissions. The transport sector, the second largest source of emissions, takes the blame mostly for vehicular emissions, especially from road transportation which accounts for 90 to 95 percent of the sector's production. While greenhouse gas emissions from road construction constitute merely 5 to 10 percent of total emissions within the sector, their trajectory is notably upward, particularly in Asia, spurred by extensive road initiatives aimed at fostering economic advancement in the region. Especially in Thailand where over 90% of paved roads are made of asphalt and the technology that Thailand has been using to produce asphalt mixture is hot mix technology which requires huge amounts of energy and fuel, especially for the processes of drying aggregates and heating asphalts which the temperature need to be maintained more than 160 °C throughout the production and construction processes. As a result, a considerable amount of GHGs is emitted in the process of generating that energy.

This study aims to assess the environmental impacts in terms of CO_2 from road construction projects in Thailand and to evaluate some existing alternative strategies to reduce CO_2 emissions from road construction activities. In term of economics, cost-effectiveness analysis is applied to determine the best-value option that minimizes CO_2 emissions and energy used.

2. LITERATURE REVIEW

A life cycle assessment (LCA) method is believed to be the best way to characterize the environmental implications of pavements (Santero et al., 2011). In the pavement construction field, there are 3 types of LCA. The first one is Cradle-to-gate, a partial Life cycle assessment covering the material production and construction phases. The second one is Cradle-to-grave, a full life cycle assessment covering material production, construction, use, maintenance, and the end-of-life phases. Lastly, Cradle-to-cradle is a closed-loop LCA where the pavement by-product is recycled or reused in material production and has a secondary life cycle instead of landfilling. Most of the previous studies categorized the emissions from pavement construction projects based on either their emissions sources or the life cycle assessment phase. For instance, In 2013, TAGG developed a guideline for GHG assessment from road construction projects. The emissions were divided into three scopes according to their sources. In 2016, a 20 km long asphalt pavement construction project was used as a case study for GHG emission assessment. Ma adopted a process based LCA method in order to assess GHG emissions from a pavement construction project. However, the study only considered 2 phases of the pavement life cycle; material production and construction. The findings indicate that the mixing and raw materials production phases collectively account for 97.12% of total GHG emissions in asphalt course construction. Specifically, 54.01% emanates from the asphalt mixture production phase, while 43.18% originates from the raw materials production phase (Ma et al., 2016).

To reduce these emissions, several technologies have been adopted. Highway industries globally have embraced warm-mix asphalt (WMA) technologies as they facilitate the production of asphalt mixtures at lower temperatures compared to traditional hot-mix asphalt (HMA). This technology adoption yields substantial advantages, primarily in fuel savings and reductions in greenhouse gas (GHG) emissions (Pouranian et al., 2019). However, these technologies come with additional costs which can significantly offset their benefits. Using waste materials in the construction and maintenance of pavements is also one of the most sustainable approaches for reducing energy consumption from virgin materials production. Especially when warm mix asphalt (WMA) technologies are used in conjunction with reclaimed asphalt pavement materials (RAP) or waste materials. The

WMA additives decrease the viscosity of the stiff binder in RAP which allows the mixture to contain more RAP. In terms of environmental benefits, this combination can reduce the emissions both from the process of raw materials production and asphalt mixture production. However, in terms of economics, only a limited number of studies have explored the economic benefits of utilizing Reclaimed Asphalt Pavement (RAP) in conjunction with Warm Mix Asphalt (WMA).

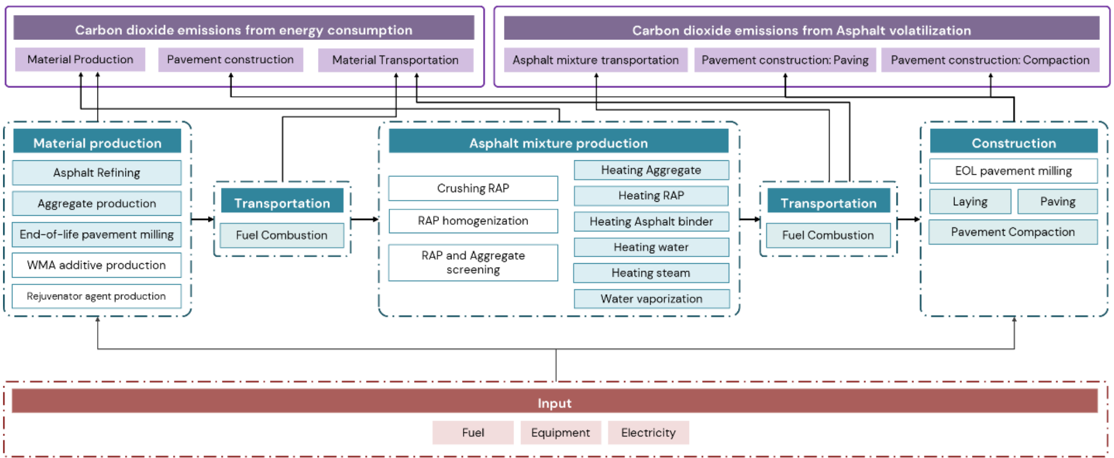
3. METHODOLOGY

3.1 Life cycle assessment (LCA)

3.1.1 Goal and scope definition

The LCA in this study has two purposes. The first one is to assess the environmental impacts of a conventional hot-mix asphalt pavement construction project or in this study, the base case, in terms of CO_2 emissions during 2 phases of its life cycle: the material production phase and the construction phase. The result from the base case will be set as the baseline for the consideration of emission reduction strategies development. The second objective is to evaluate the CO_2 emissions from the alternative strategies to determine the most appropriate solution for CO_2 emissions reduction.

The life cycle of asphalt pavements generally includes six phases: construction materials production, pavement construction, operation, maintenance, and end-of-life. However, this study will focus on the material production and construction phases in which most energy consumption occurs. The first phase, material production, will be separated into two sub-phases: raw material production and asphalt mixture production. This will highlight the influence of asphalt production temperature due to the technology on the overall impact. However, as presented in Figure 3.1, due to the lack of information on the production processes of some materials such as WMA additives and Rejuvenator agents, those processes shall be neglected in this study. The reclaimed asphalt pavement (RAP) is assumed to be ready to use or so-called classified RAP. Therefore, only heating processes in asphalt plants will be considered in this study. In case of the construction phase, this study primarily concentrates on the process of laying, paving, and compacting asphalt mixture.



Note: Only the highlighted processws are considered in this study.

Figure 3. 1 LCA system boundary

Therefore, the CO_2 emissions in this study are categorized into two scopes based on their sources. The first scope covers all energy consumption emissions, including CO_2 from materials production, pavement construction, and materials transportation. The other one is asphalt volatilization which occurs in asphalt mixture production, transportation, and construction processes. However, in this study, the dust collector system of the asphalt plant is assumed to be fully efficient. Hence, the volatilization from asphalt mixture production is neglected.

This study considers a section of road 1 Km long with a travelway width of 13m. and a thickness of the asphalt surface layer of 0.05 m as the functional unit. Nevertheless, to illustrate the magnitude of CO_2 emissions released compared to the quantity of asphalt mixture used in construction, the CO_2 emissions at the end will be presented in the unit $kgCO_2$/1000ton of asphalt mixture.

3.2.2 Life cycle inventory (LCI)

Life cycle inventory is the step in which the information will be sorted as input to the CO_2 emissions calculation model. In this study, life cycle inventory will be divided into two parts which are data collection and CO_2 emission modeling.

3.1.2.1 Data collection

Most of the data is based on the construction sheet from a pavement construction project of the Department of Highway (DOH), Thailand. However, since warm-mix technologies are merely used in Thailand, the data on the additives, such as the dosage along with the additives cost, plant modification cost, and transportation cost, need to be referenced from the previous study. The amount of materials used for asphalt mixture production is based on the job mix design received from the Department of Highway (DOH), Thailand. Each material shall be described in percentages by weight of the asphalt mixture. The asphalt plant is assumed to be a batch plant since most of the asphalt plants in Thailand are batch plants. The data on the set of equipments required for the surface course construction along with their productivity and fuel efficiency are based on the construction criteria from the Department of Highways (DOH).

3.1.2.2 CO_2 emissions modeling

In this study, the CO_2 emissions model is developed on Microsoft Excel as a tool to calculate the emissions from each case. There are 2 separate models developed for each scope of CO2 emissions: CO_2 emissions from energy consumption which the model was adopted from previous studies by Aurangzeb et al. (2014), Sukhija et al. (2022), and CO_2 emissions from asphalt volatilization in which the calculation models used in this study is adopted from Peng, et al. (2020). The equations for the emission calculation of each model are presented in Table 3.7-3.10

Table 3.1 shows the parameters that need to be varied in each case, which are job mix inputs. The rest are fixed parameters which are presented in Table 3.2-3.6

Table 3. 1 Variable inputs for CO_2 emissions modeling

Catagories	Type of input	Variables	Unit
Acitvity data INPUT	Job mix INPUT	Mass of asphalt mixture	Ton
		%Reclaimed asphalt pavement (RAP)	% by weight of asphalt mixture
		%Remained asphalt in RAP	% by weight of asphalt mixture
		Type of asphalt binder	-
		%Optimum binder	% by weight of asphalt mixture
		%Rejuvenator agent	% by weight of asphalt mixture
		Type of WMA additive	-
		% WMA additive	% by weight of asphalt binder
	Mix production	%Moisture content of each material	%

INPUT		Ambient temperature	°C
		Heating temperature for aggregate and binder	°C
		Heating temperature for Reclaimed asphalt pavement (RAP)	°C
Asphalt volatilization INPUT	Transportation process	Temperature of asphalt mixture during transportation	°C
	Paving process	Temperature of asphalt mixture during paving	°C
	Compaction process	Temperature of the asphalt mixture during compaction	°C

Table 3. 2 Material characteristics

Variables	Notations	Unit	Value	Reference
Ambient Temperature	t_a	°C	30	Sukhija et al. (2022)
The boiling point of water	t_b	°C	100	Sukhija et al. (2022)
Specific heat of RAP	S_r	J/kg.°C	900	FHWA,USA
Specific heat of aggregates	S_a	J/kg.°C	850	Sukhija et al. (2022)
Specific heat of water	S_w	J/kg.°C	4200	Sukhija et al. (2022)
Specific heat of steam	S_s	J/kg.°C	1825	Sukhija et al. (2022)
Specific heat of asphalt binder	S_b	J/kg.°C	2093.4	Sukhija et al. (2022)
Moisture content in aggregates	m	%	2	Construction sheet, DOH
Latent heat of vaporization	L_v	J/kg	2,250,000	Sukhija et al. (2022)
Mass of asphalt mixture	M_T	kg	1000	Construction sheet, DOH
Optimum binder content	OBC	%	5.8	Construction sheet, DOH
Mass of aggregates	M_a	kg	942	Construction sheet, DOH
Mass of asphalt binder	M_b	kg	58	Construction sheet, DOH

Table 3. 3 Combustion Emission factors (TGO)

Combustion activity	Type of fuel	CO_2 Energy emission factor (EEF)	Unit
Stationary combustion	Furnace oil	72930	Mg/MJ
Mobile combustion	Diesel (dump truck)	2.7	kgCO_2/litre

Table 3. 4 Materials emission factors

Materials	CO_2 Emission factor (EF)	Unit	Reference
Asphalt binder	190.9	$kgCO_2$/ton	Eurobitumen
Aggregate	0.0037	$kgCO_2$/kg	EPA
Diesel	0.3743	$kgCO_2$/kg	TGO
Furnace oil	0.3522	$kgCO_2$/kg	TGO

Table 3. 5 Equipment data (Construction Criteria, DOH)

Equipment	Number of equipments	Productivity; p (ton/hr)	Fuel type	Fuel efficiency; f (L/hr)
Wheel loader	1	60	Diesel	12
Rubber tire roller	3	20	Diesel	8
Vibrating Roller	1	60	Diesel	13
Steel Wheel Roller	1	60	Diesel	8
Water truck	1	60	Diesel	12
Power broom	1	60	Diesel	6.5
Air blower	1	60	Diesel	8.5
Asphaltic concrete paver	1	60	Diesel	10.5
Electricity generator	1	60	Diesel	35

Table 3. 6 Material transportation data

Materials		Unit	Distance	References
Supplier to asphalt plant				
AC 60/70		Km	335	Construction sheet
AC40/50		Km	335	Construction sheet
PMA		Km	335	Construction sheet
Rejuvenator agent		Km	598	Construction sheet
WMA additive		Km	598	Assumed
Aggregate	¼"	Km	38	Construction sheet
	¾"	Km	31	Construction sheet
	3/8"	Km	31	Construction sheet
Asphalt plant to construction site				
Asphalt mixture		Km	5	Construction sheet

Table 3. 7 CO_2 emissions model for energy consumption

CO_2 Emissions from energy consumption (CE_{eng})	Equation
Total CO_2 from energy consumption (CE_{eng})	$CE_{eng} = CE_1 + CE_2 + CE_3$
CO_2 from material production (CE_1)	$CE_1 = CE_{raw} + CE_{mix}$
CO_2 from Raw material production (CE_{raw})	$CE_{raw} = \sum_{i=1}^{n} CE_{raw\,i} = \sum_{i=1}^{n} (EF_i \times u_i)$
CO_2 from Asphalt mixture production (CE_{mix})	$CE_{mix} = F \times \Phi \times \rho \times \alpha \times EEF$
CO_2 from construction process (CE_2)	$CE_2 = \sum_{i=1}^{material} \sum_{j=1}^{equipment} \left(\frac{m_i \times f_i \times EF}{p_j} \right)$
CO_2 from construction process (CE_3)	$CE_3 = \sum_{i=1}^{material} \sum_{j=1}^{equipment} \left(\frac{m_i \times f_i \times d_j \times EF_{ft}}{p_j} \right)$

Table 3. 8 Equations for energy consumption calculation

Variables	Equations
Heating aggregates (H_a)	$H_a = S_a \times M_a \times T_a \times (T_a - t_a)$
Heating reclaimed asphalt pavement (H_s)	$H_s = S_a \times M_a \times T_s \times (T_s - t_a)$
Heating water (H_w)	$H_w = S_w \times \frac{m}{100} \times M_a \times (t_b - t_a)$
Water vaporizsation (H_v)	$H_v = L_v \times \frac{m}{100} \times M_a$
Heating steam (H_s)	$H_s = S_s \times \frac{m}{100} \times M_a \times (T_a - t_b)$
Heating asphalt binder (H_b)	$H_b = S_b \times M_b \times (T_b - t_a)$
Total	$H = H_a + H_w + H_v + H_s + H_b$
Fuel Consumption	$F = \frac{H}{\Phi \times \rho}$

Table 3. 9 CO_2 emissions model for asphalt volatilization

Asphalt volatilization model	Equation
Total emissions from asphalt volatilization	$CE_{vol} = CE_4 + CE_5 + CE_6$
CO_2 from Asphalt mixture transportation (CE_4)	$CE_4 = \frac{S_1 \times v_1 \times t_1 \times (\rho_1(t) \times GWP)}{10^6 G_1}$

CO_2 from Asphalt mixture Paving (CE_5)	$CE_5 = \frac{v_2 \times t_2 \times y_1 \times \int_0^{x_1} \rho_2(x) \times GWP\, dx}{10^6 G_2}$
CO_2 from Rolling compaction (CE_6)	$CE_6 = \frac{v_3 \times x_1 \times y_1 \times \int_0^{t_3} \rho_3(t) \times GWPdt}{10^6 G_2}$

Table 3. 10 Gas mass concentration ad Diffusion rate equations

Asphalt volatilization model	Equation
Gas mass concentration for paving	$\rho_2 = -0.3732x_1^2 + 5.9405x_1 + 603.58$
Gas mass concentration for Compaction	$\rho_3 = 9 \times 10^{-5}t_3^2 - 0.2932t_3 + 609.28$
Gas diffusion rate	$v = 3 \times 10^{-6}T_i^2 + 0.0022T_i + 0.1078$

3.2 Cost-effectiveness Analysis

In the context of pavements and greenhouse gas (GHG) emissions, applying the concept of cost-effectiveness involves evaluating reduction strategies based not only on their potential to reduce emissions but also on the relative cost of achieving those reductions. Therefore, in this study, cost-effectiveness refers to the cost associated with reducing CO_2 emissions.

The costs in pavement construction projects can be separated into 4 groups: material cost, asphalt plant operation cost, construction cost, and material transportation cost. However, since there is no evidence of how the alternative strategies can lower the construction cost, the construction cost shall be the same in every case. In terms of the benefit, only the amount of CO2 reduction from each alternative case will be accounted as the benefit in this study. The cost-effectiveness can be calculated based on the equation below which is referenced from a study by Santero et al. (2013).

$$CE_{alt} = \frac{cost_{alt} - cost_{ctrl}}{emissions_{alt} - emissions_{ctrl}}$$

Where CEalt is the total cos-effectiveness of each alternative
$cost_{alt}$ is the total cost of the alternative
$cost_{ctrl}$ is the total cost of the base case (convention HMA of AC60/70)
$emissions_{alt}$ is the emissions from alternative case
$emissions_{ctrl}$ is the emissions from the control case

3.3 Cases summary

3.3.1 Reference project

A hot-mix asphalt pavement construction project of the Department of Highway (DOH), Thailand is taken as the referenced site for the case study. The project was originally a hot in-plant rehabilitation project, located in Nong Bua Lam Phu, covering a section of road approximately 1 km long, 13 m wide, and 5 cm thick.

3.3.2 Base cases

The base cases of the study resemble the 3 types of binders used in the Department of Highway Thailand which include AC40/50, AC60/70, and PMA. The details of each case will be presented in Table 3.11.

Table 3. 11 Base cases summary

No.	Mix code	Mix technology	Binder type	RAP content
1	aH0RAP	HMA	AC60/70	0
2	bH0RAP	HMA	AC40/50	0
3	PMA	HMA	PMA	0

3.3.3 Alternative cases

For the alternative strategies, this study focuses on warm mix asphalt technology to reduce the energy consumption and emissions from the process of drying and heating mineral aggregates in the material production phase and the use of reclaimed asphalt pavement (RAP) to substitute a certain amount of the fresh aggregate and virgin asphalt. As shown in Table 3.12, three types of warm mix technologies along with their dosages are investigated to highlight the temperature reduction range of each type of technologies.

For Reclaimed asphalt pavement content, the amount varies between 0% and 40%. Therefore, a total of 14 alternative cases will be analyzed in terms of CO_2 reduction potential. The details of each case are provided in Table 3.13.

Table 3. 12 WMA additives

WMA additives	Technology	Dosages	Mixing temperature	
			AC60/70	AC40/50 and PMA
Sasobit	Organic/wax	3%	135	155
Evotherm	Chemical	5-8%	105	125
Advera	Foaming	0.5%	135	155

Table 3. 13 Alternative cases summary

NO.	Mix Code	Mix technology	Binder type	Additives	RAP content
1	aH40R	HMA	AC 60/70	Rejuvenator agent	0
2	bH40R	HMA	AC 60/70	Rejuvenator agent	40
3	aSW0R	WMA (wax)	AC 60/70	Sasobit	0
4	aEW0R	WMA (chemical)	AC 60/70	Evotherm	0
5	aAW0R	WMA (foaming)	AC 60/70	Advera	0
6	bSW0R	WMA (Wax)	AC 40/50	Sasobit	0
7	bEW0R	WMA (chemical)	AC 40/50	Evotherm	0
8	bAW0R	WMA (foaming)	AC 40/50	Advera	0
9	aSW40R	WMA (wax)	AC 60/70	Sasobit	40

10	aEW40R	WMA (chemical)	AC 60/70	Evotherm	40
11	aAW40R	WMA (foaming)	AC 60/70	Advera	40
12	bSW40R	WMA (wax)	AC 40/50	Sasobit	40
13	bEW40R	WMA (chemical)	AC40/50	Evotherm	40
14	bAW40R	WMA (foaming)	AC 40/50	Advera	40

4. RESULTS AND DISCUSSIONS

4.1 Life cycle assessment (LCA) results

The CO_2 emissions presented in Figures 4.1 and 4.2 are separated into 2 categories. The first one is CO_2 emissions from energy consumption and the next one is CO_2 emissions from asphalt volatilization. The CO_2 from energy consumption includes 4 components: Raw material production, Asphalt mixture production, Asphalt pavement construction, and Materials transportation. For asphalt volatilization, the results are divided into three groups: asphalt volatilization during the process of asphalt mixture transportation to the construction site, during the paving process, and during the compaction process.

As presented in Figures 4.1 and 4.2, the results show that for conventional HMA, the total CO_2 emissions are released at the rate of 35,000 $kgCO_2$/1000-ton asphalt mixture. It can also be observed that in every case, most of the CO_2 emissions are from energy consumption in both raw materials production and asphalt mixture production processes. On the other hand, for both AC60/70 and AC40/50, it can be noticed that the amount of CO_2 emissions from asphalt volatilization is very little compared to those from energy consumption. In addition, cases in both AC60/70 and AC40/50 show the same trend of CO_2 emissions reduction.

For the alternative cases in which reclaimed asphalt pavement (RAP) is implemented, the results show that, in comparison with the conventional hot-mix asphalt (HMA), nearly 30% of CO_2 emissions were reduced from the raw materials production processes. However, those benefits were offset by the excessive CO_2 emissions from supplementary material (e.g. Rejuvenator agent) transportation. As a result, only 10% of total CO_2 emissions were reduced.

For cases with warm mix asphalt (WMA) additives, as presented in the below figures, all three binders significantly reduce CO_2 emissions from the asphalt mixture production process. Especially for Evotherm, which performs the best in both AC60/70 and AC40/50 binders, has reduced by 32.25% and 29.12% respectively. However, in terms of CO_2 emissions from asphalt volatilization, even though the mixing temperature was dropped lower than 130°C, the total CO_2 emissions from asphalt volatilization only reduced by 2.47-5.61%. It should also be noted that the CO_2 emissions from asphalt volatilization only account for 3% of the total CO_2 emissions. Therefore, in this study, the emissions in the asphalt volatilization part can be ignored. Moreover, the benefits of these additives were offset by the amount of CO_2 emissions released during the transportation process of the additives. As a result, in total, for AC60/70 binder, Sasobit, Evotherm, and Advera can reduce CO_2 emissions by 5.6%, 12.27%, and 5.58% respectively. For AC40/50 binder, 5.32%, 9.96% and 5.89% respectively.

Lastly, when RAP materials are implemented with WMA additives, It can be seen that the most successful case is Evotherm with 40% reclaimed asphalt pavement (RAP) which can reduce the CO_2 emissions in total by 22.9% for AC60/70 and 21.33% for AC40/50.

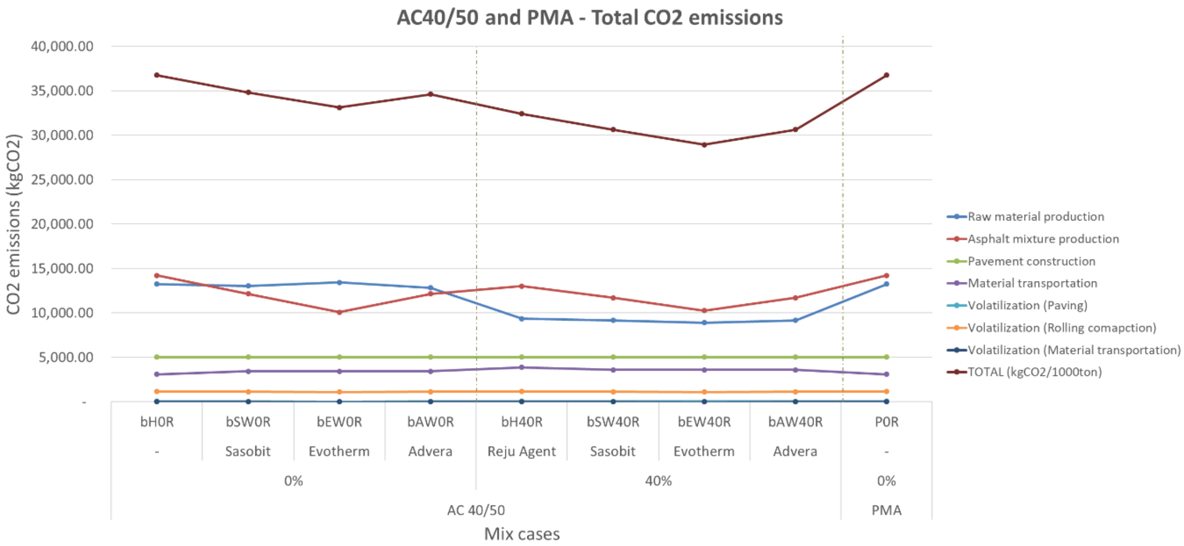


Figure 4. 1 CO2 emissions (AC40/50 and PMA)

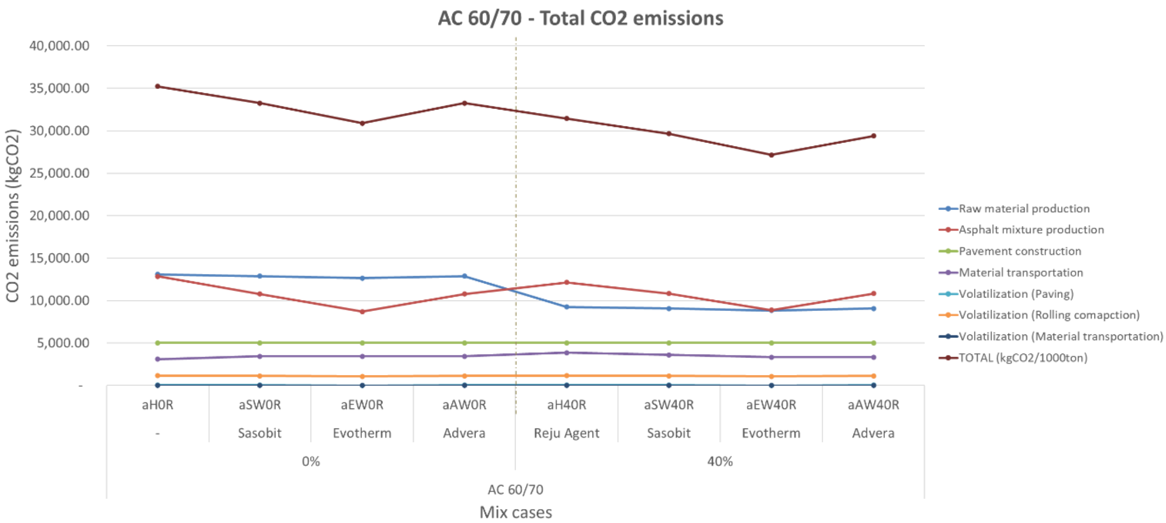


Figure 4. 2 CO2 emissions (AC60/70)

4.2 Cost-effectiveness analysis

For both AC60/70 and AC40/50, 4 cases have negative cost-effectiveness values which can be attributed to their ability to not only reduce CO_2 emissions but also lower overall project costs. The value is described as net cost savings. These cases include EW0R which is an Evotherm mix with 0% RAP, H40R which is HMA with 40% of reclaimed asphalt pavement (RAP), and EW40R which is an Evotherm mix with 40% of reclaimed asphalt pavement (RAP). Among those cases, the most successful alternative in both binders is Evotherm with 40% RAP which can reduce the CO_2 by 22.89% and 21.33% in AC60/70 and AC40/50 respectively. In terms of cost savings, the mix can reduce the cost by 32.43% and 32.61% in AC60/70 and AC40/50 respectively.

5. CONCLUSIONS AND LIMITATIONS

5.1 Conclusions

In this study, the environmental impacts of 3 base cases and 14 alternative cases are assessed using the Life Cycle Assessment (LCA) method, with Microsoft Excel utilized as the analytical tool. The results obtained from the base cases establish the threshold, as the study aims to identify the optimal solution for reducing CO_2 emissions in pavement construction projects. Subsequently, the reduction in CO2 emissions is treated as a benefit in the cost-effectiveness analysis, allowing for an evaluation of the most suitable alternative in terms of both environmental and economic considerations. The results of the study can be concluded as follows:

- For conventional HMA, CO_2 emissions are primarily released from two main processes: raw material production and asphalt mixture production. In asphalt mixture production, more than 60% of the CO_2 comes from heating aggregates followed by 24% from water vaporization.
- By using reclaimed asphalt pavement (RAP) as the substituted material, the CO_2 emissions were significantly reduced in the process of raw materials production by 30%. However, due to the process of reclaimed asphalt pavement (RAP) transportation, the benefit of RAP substitution was offset. In total, this strategy can reduce CO_2 emissions by 10-15%.
- Among the three types of warm mix additives, Evotherm performs best in emissions reduction in the asphalt mixture production process. However, the benefits of these additives were offset by the amount of CO_2 emissions released during the transportation process of the additives. As a result, WMA technologies only reduce the emissions by 5-12%.
- When RAP was used and incorporated with WMA additives, the most successful case is Evotherm with 40% reclaimed asphalt pavement (RAP) which can reduce the CO_2 emissions in total by 22.9% for AC60/70 and 21.33% for AC40/50 compared to the base case of each binder.
- Both AC40/50 and AC60/70 have the same trend of CO_2 emissions reduction.
- Regarding economic analysis, the most promising case is the case that incorporates Evotherm and RAP materials.

5.2 Limitations of the studies and recommendations

Due to the limited data, this research has several gaps to fill. For the next research, here are some recommendations.

- The operation and maintenance phases should be considered in Life cycle assessment (LCA) to assess the emissions from the whole life cycle.
- Due to the lack of a pavement deterioration model, the performance of each mixture can not be predicted. Therefore, the service life of each alternative was assumed to be the same.
- This research only measured environmental impacts in terms of CO_2 emissions. However, other GHG emissions such as N_2O, and CH_4 also cause serious problems. Therefore, the rest of the GHG emissions should be considered.
- Sensitivity analysis should be conducted in terms of changes in transportation distance, and changes in moisture content in each material.
- This study did not cover the process of warm mix additives production. Therefore, the benefit of using the technologies could be offset.

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Adoption of Carbon Mineralised Concrete for Precast Concrete Segments in Singapore North-South Corridor Project

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ABSTRACT

The North-South Corridor (NSC) is a 21.5km long road connecting the Northern region and city centre of Singapore. NSC involves the construction of 12.3km underground road tunnel, 0.4km at-grade road and 8.8km road viaduct. When completed, NSC will become Singapore's first multi-modal Land Transport Corridor, comprising of dedicated bus lanes, cycling trunk routes and pedestrian paths as well as more communal and green spaces. This is made possible by expanding the road network system above and underground so that precious surface land can be freed up, given the increasing population on a land-scarce island like Singapore.

Globally, the built environment generates 40% of annual anthropogenic CO_2 emission. Unlike operational carbon emissions, which can be reduced over time with electrical upgrades and the use of renewable energy, embodied carbon emissions are locked in place as soon as a structure is built. As NSC's 8.8km road viaduct is primarily constructed using precast segmental box girders, carbon mineralised concrete can be adopted to reduce the embodied carbon in the box girders. This is in line with Singapore's sustainability drive towards a net zero emission target by 2050.

Carbon mineralised concrete utilises a technology which traps carbon dioxide by first converting pressurised carbon dioxide gas into dry ice consistency, before mixing it with the other aggregate and cementitious materials during the concrete batching process. This causes the cement paste to mix with the injected carbon dioxide, creating nano-mineral calcium carbonate, which is permanently embedded in the concrete. In NSC, a total of 2900 units of segmental box girders, with a total estimated concrete volume of 107,400m^3, will be precasted for the viaduct using this technology. The paper presents the considerations for carbon mineralised concrete, potential benefits in adopting this technology and early-stage results (in terms of strength, physical properties, workability).

Keywords Green concrete, Precast concrete technology, Carbon mineralised concrete

1. INTRODUCTION

Concrete is the second most widely used material in the world after water and has been used in many structures since the time of the Romans. It is strong, durable and malleable, making it a very popular construction material. The raw materials of concrete (sand, rock, lime and water) are also easily sourced in nature. However, with rapid urbanisation in the past century, there has been a significant increase in the use of concrete for various infrastructure from roads to buildings and canals. At the same time, the pace of climate change has been picking up with rapid industrialisation all over the world. By some estimates, about 7 to 8% of the carbon emission worldwide is contributed by concrete production alone (Vargas, 2023), and the bulk of it comes from cement production, which accounted for 90% of the carbon footprint of concrete (Skinner & Lalit, 2023).

It is crucial for the built environment to rapidly de-carbonise and reduce the amount of carbon emissions generated. Of the potential possibilities, one of the more attractive ones is Carbon Capture, Utilisation and Storage (CCUS) (Vargas, 2023), which is to capture carbon from industrial processes by converting it to nano-mineral calcium carbonate and storing it within the concrete. This helps to trap the carbon within the concrete, preventing it from being released into the air and contributing to carbon emissions.

On top of trapping the carbon emissions permanently, a major benefit of this process is that cement reduction can be achieved without compromising the strength or elastic moduli of the concrete (Monkman, Cialdella, & Pacheco, 2023). For the North-South Corridor project, the local concrete supplier estimated that the amount of cement required in the concrete can be reduced by around 5%. This is because nano-mineral calcium carbonate densifies the cementitious matrix, improving the porosity of the concrete (Wang, et al., 2017) and acts as a fine filler formed in-situ with the Calcium Silicate Hydrates (CSH) gel (Zajac, Skocek, Haha, & Deja, 2022). The strength of bond between the cementitious material and aggregate thereby improves. Similar compressive strength and elastic moduli can thus be achieved with reduction in cement content, which provides significant reduction in carbon emissions as cement production is the main bulk of the carbon emissions in concrete production.

Nonetheless, with any new technology, there would be some resistance in the execution of this product. The purpose of the paper is to elucidate the concept of carbon mineralised concrete and establish a pathway towards successful implementation of carbon mineralised concrete for precast segmental box girders.

This paper will first introduce the concept of carbon mineralised concrete and benefits observed. We would further establish the trial carbon mineralised concrete mix used for this project, the initial validation testing for the product, and subsequent casting results and observations, with an aim to conclude with considerations for the implementation of carbon mineralised concrete for precast viaduct construction.

2. CONCEPT OF CARBON CAPTURE AND UTILISATION

The mechanism behind concrete hardening is well-known throughout the industry. Concrete develops its strength through the development of hydration products such as CSH gel when water reacts with cement. The CSH gel binds the aggregates together and provide strength to the concrete by filling the spaces between the cement particles and surface of the concrete aggregate. Additionally, calcium hydroxide (otherwise known as Portlandite) is also formed, filling in the voids in the concrete matrix. After initial setting of the concrete, in the presence of sufficient moisture, more CSH and calcium hydroxide would continue to develop over the next few weeks, thus the strength of the concrete increases as the hydration products bind the cement and aggregate together. The hydration of cement to form CSH and calcium hydroxide (Portlandite) is shown in Figure 1 below.

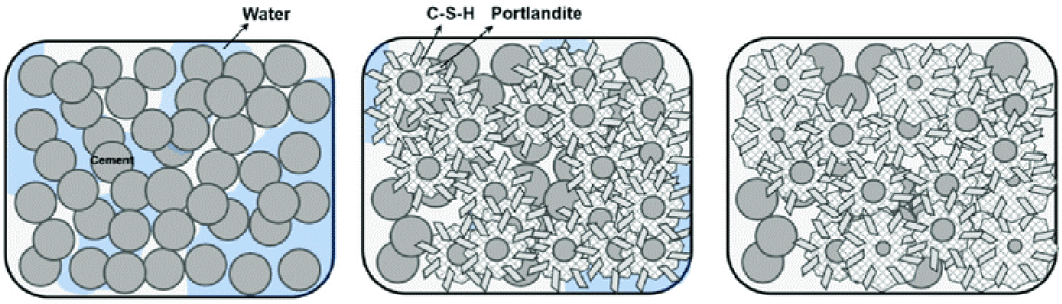

Figure 1: Schematic of concrete hydration process - aggregate not shown (Lee, Jeong, Kang, & Moon, 2020)

Compared to the history of concrete, the development of carbon mineralised concrete is recent. The first commercial use of carbon mineralised concrete was around 2012 for concrete paving and minor civil works. The first major construction project using carbon mineralised concrete was a 3,000 m^2 Canadian tour bus company comprising of its headquarters and garage constructed in 2016. Some significant projects using carbon mineralised concrete in Singapore include a 7-hectare conglomerate office campus, a 200m tall office tower, a 1074-unit condominium, and an upcoming port in Tuas, Singapore.

There is a gradual adoption process throughout Asia as more and more concrete producers have started to produce carbon mineralised concrete mix. For instance, Korea is completing a 28,770 m^2 television studio complex using carbon mineralised concrete. Going forward, more projects would start to use carbon mineralised concrete, with sustainability in mind.

The idea of carbon mineralised concrete is rather straightforward. The process involves injecting carbon dioxide, which is usually obtained as by-products of industrial processes. (In Singapore's case, it is the petrochemical industry.) The carbon dioxide is first pressurised and liquefied into dry ice. The liquid dry ice is then mixed in during the concrete batching process to form nano-crystalline calcium carbonate minerals with the calcium hydroxide (Portlandite) present in the cement paste (CarbonCure Media Team, 2023). As the calcium carbonate mineral has a higher molar mass, it can more easily fill the gaps within the cementitious matrix and bind the cement and aggregates together.

Figure 2: Carbon mineralisation process (The Institution of Engineers, Singapore, 2021)

Furthermore, the larger size of the calcium carbonate particles acts as nucleation sites for the hydration process, allowing for accelerated hydration. Thus, a lower water-cement ratio can be used for concrete batching without compromising the concrete strength.

The key to the success of carbon mineralised concrete lies in its ability to reduce the cement content, which is the chief contributor to carbon emissions from concrete production and the built environment industry, with an estimated 92% of embodied carbon emissions from the entire concrete manufacturing process stemming from cement production alone (National Ready Mix Concrete Association, 2008).

Tests by Monkman et al. (2023) in USA have revealed that up to 7% reduction in cement content was achievable through the injection of liquid carbon dioxide without compromising the strength or durability of the concrete. There was also no change in the surface resistivity, drying shrinkage and rapid chloride permeability test performance (Monkman et al. , 2023). Tests conducted in Australia (Tam, Butera, & Le, 2023) also indicated that carbonation helped to improve the shrinkage and durability performance for similar concrete mixes.

However, there were concerns raised by various authors on the use of carbon mineralised concrete. As carbon dioxide is acidic in nature, there might be a risk of increased corrosion to the reinforcement bars in the long term (Ahmad, 2006). Furthermore, there is a decrease in cement content compared to traditional concrete mixes. Therefore, validation testing was performed to determine the effect of carbon mineralisation on the physical properties and material characteristics of the concrete before casting the box girder segments.

3. MATERIAL AND METHODS

3.1 Trial mix

The initial validation testing process was as follow. The trial mix of the carbon mineralised concrete, known as CEN8613, was designed based on the design strength of C45/55 (characteristic cube strength at 28 days = 55 MPa). The mix parameters are listed below. Retarder ADVA 181, superplasticiser ADVA181N and liquid carbon dioxide (99% purity) was added into the concrete mix, and the mix was designed for a target slump of 200 to 250mm. It was expected that the concrete would attain an early-stage strength of 12 MPa within 12 hours of casting to allow for de-moulding of the precast segment. This was compared to a control mix of normal concrete known as EN8663 with similar characteristics (slump and early-stage strength) to assure that the strength, permeability, elastic modulus, creep and shrinkage were comparable to normal concrete. It is noted that the carbon mineralised concrete has 5% less Ordinary Portland Cement (OPC) content compared to normal concrete and hence, the water-to-cement ratio of CEN8613 is slightly higher than that of EN8663. A summary of the trial mixes is presented in Table 1 below.

Table 1 Trial Mix Content.

Mix Reference		**Carbon Mineralised Concrete (CEN8613)**	**Normal Concrete (EN 8663)**
Material	**Class**		
Ordinary Portland Cement	CEM IIB, 42.5N	380kg/m^3	400kg/m^3
Ground Granulated Blast Slag (GGBS)	-	130kg/m^3	130kg/m^3
Water	-	160kg/m^3	160kg/m^3
Coarse Aggregate	4mm to 20mm G_c = 90/15	1000kg/m^3 (saturated surface dry (SSD) state)	1000kg/m^3 (SSD state)
Fine aggregate	0mm to 4mm, G_f = 85	710kg/m^3 (SSD state)	690kg/m^3 (SSD state)
Retarding Superplasticiser	ADVA181	2.04L/m^3	-
Superplasticiser	ADVA181N	3.06L/m^3	5.30L/m^3
Liquid Carbon dioxide	99% purity	0.76 kg/m^3	-

3.2 Precast segmental box girder dimensions

Upon validation of the trial mix, the precast box girder segments were then casted with carbon mineralised concrete. The segments casted were two-cell box girders, with a top flange thickness of 300 to 600 mm, side web thickness of 350 to 650 mm, centre web thickness of 350 to 650 mm, and bottom web thickness of 300 to 400 mm. A schematic of the section is shown below for info. The weight of each segment is between 67 and 120 tons. The length of each segment is between 2.5 m and 3.2m. The height of each segment ranges from 2.2m to 4.0m and the width of each segment ranges from 13m to 19m. This is illustrated in Figure 3a & 3b below.

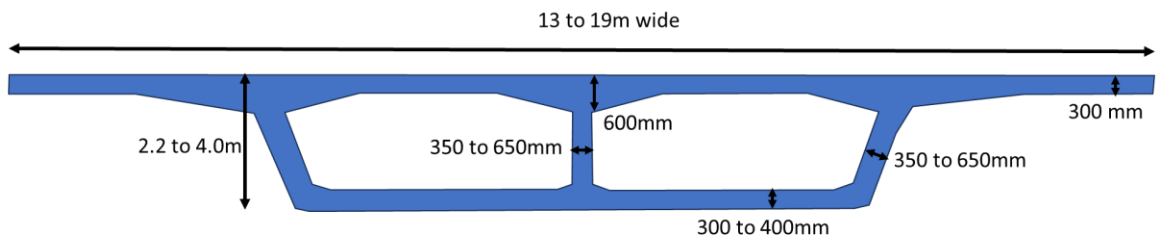

Figure 3a Schematic of the precast box girder segment.

Figure 3b Photograph of actual segment casted.

The results of the compressive strength (12 hours, 3 days, 7 days and 28 days) and the slump from the actual concrete mix delivered to site would be presented to provide confidence to practitioners on the use of carbon mineralised concrete for large precast segments.

4. RESULTS

4.1 Validation testing

Validation testing was conducted based on relevant British Standards (BS) or ASTM International Standards. Results were then compared to the BS/ASTM requirements or Professional Engineer (PE)'s requirements which are based on Eurocode 2 (EC2) design. The following requirements were assessed:

- Physical properties (Bulk density)
- Mechanical properties (Compressive strength, elastic modulus, splitting tensile strength)
- Time-dependent properties (Creep and shrinkage)
- Permeability and durability (Rapid chloride permeability, water penetration, acid resistance, carbonation depth, pore solution alkalinity)

A summary of the validation testing results is presented below in Table 2.

Table 2 Validation Testing Results.

Mechanical Property (Units)	Test Standard	Test Age	Carbon Mineralised (CEN8613)	Normal Concrete (EN8663)	Standards / PE requirements
Dry bulk density (*kg m*)	ASTM C642-21	31 days	2192	2177	For cross-comparison with normal concrete
Compressive Strength (*MPa*)	BS EN 12390-3: 2019	12 h	14.3 (s.d.=0.6)	14.1 (s.d. =0.8)	15.0 (de-moulding specified by PE)
		36 h	35.3 (s.d. =1.1)	33.4 (s.d. =0.8)	For cross-comparison with normal concrete
		3 days	48.9 (s.d. =0.8)	46.5 (s.d. =1.2)	For cross-comparison with normal concrete
		7 days	68.0 (s.d. =6.1)	68.8 (s.d. =1.4)	For cross-comparison with normal concrete
		28 days	78.7 (s.d. =5.2)	78.0 (s.d. =2.2)	55.0 (28 days strength specified by PE according to EC2 design)
Elastic modulus – secant modulus of elasticity (*GPa*)	BS EN 12390-13: 2021 – Method B	28 days	36.2	36.5	36.0 (according to EC2 design, $E_{cm} = 22000\left(\frac{f_{cm}}{10}\right)^{0.3}$)
Creep – creep coefficient	ASTM C512/C512M-15	28 Days Curing + 90 Days	1.19	1.20	1.36 (according to EC2 Annex B)
Shrinkage (*strain x*)	ASTM C157/C157M-17	28 Days Curing + 90 Days	811	267	204 (according to EC2 Annex B)
Tensile strength – splitting tensile strength (*MPa*)	BS EN 12390 – 6: 2009	28 days	4.5	4.5	For cross-comparison with normal concrete
Flexural strength (*MPa*)	BS EN 12390 – 5: 2009	28 days	6.7	6.7	For cross-comparison with normal concrete
Permeability Voids (%)	ASTM C642-21	31 days	11.1	10.8	For cross-comparison with normal concrete
Absorption after immersion and autoclave (%)	ASTM C642-21	31 days	5.1	4.9	For cross-comparison with normal concrete
Permeability – water penetration depth (*mm*)	BS EN 12390-8: 2019	28 days	14.0	15.3	For cross-comparison with normal concrete
Diffusivity – Rapid chloride penetration test (*Coulombs*)	ASTM C1202-12	28 to 31 days	2710	2836	For cross-comparison with normal concrete
		60 to 61 days	1942	2015	For cross-comparison with normal concrete
Sulphate resistance – length change (%)	ASTM C1012/C1012M-18b	42 days	+0.074	+0.081	For cross-comparison with normal concrete
Acid resistance – compressive strength (*MPa*)	ASTM C267-12	14 days curing + 28 days acid exposure	52.0	43.0	For cross-comparison with normal concrete
Carbonation resistance – Carbonation depth (*mm*)	BS1881 Part 210: 2013	16 days curing + 34 days carbonation exposure	0.8	0.9	For cross-comparison with normal concrete
Rebar corrosion potential – half cell potential, Cu-$CuSO_4$ electrode (*m*)	ASTM C876-15	96 days	-10	-25	> -200 (to confirm improbable corrosion)
Pore solution alkalinity	-	28 days	13.46	13.39	>12.5 (for passivation of carbonation induced corrosion)

Note:
s.d. = standard deviation

From validation testing, it appears that there are some slight benefits to the permeability and durability of the concrete when using carbon mineralised concrete, as seen from the lower charge passing through during the rapid chloride penetration test, lower water penetration, lower rebar corrosion potential and lower length change when the sample was exposed to sulphate attack. This may be attributed to the larger molar mass of the calcium carbonate crystals (compared to calcium hydroxide crystals in normal concrete) closing up the pores in the cementitious matrix when using carbon mineralised concrete.

We do note that there could be potential issue with the early shrinkage of carbon mineralised concrete (811 micro-strains) as it is more than the requirements (204 micro-strains). This is common among concrete with admixtures added due to increase in volume of fine pores when admixture is added (BASF Group, 2016). It is also known that carbonation increases shrinkage as it affects the bonding characteristics of the CSH gel (Verbeck, 1958).

However, among high-performance and admixture-entrenched concrete, such shrinkage values are not uncommon, and it can be mitigated with proper workmanship to avoid issues such as cracking, which are caused by restraint to the concrete during the curing process.

Furthermore, the eventual prestressing of the segments during viaduct box girder segment launching would help to close up any hairline cracks that could be formed. Minor cracks could also be repaired and patched with grout or other materials. The presence of significant reinforcement within the box girder segments also helps to restraint any potential cracking of the segment unlike a monolithic concrete slab.

While some dimensional instability could be expected from higher shrinkage (BASF Group, 2016), resulting in loss of prestressing application and potential curling of the segments and slabs (BASF Group, 2016), so long the segments are casted in advance and left to cure for some time (typically 2-3 months before launching), there should be no significant change in the segment dimensions by the time the segments were launched since shrinkage is an early-stage property.

In addition, to mitigate any curling of the precast segment, it is important to minimise moisture and temperature differentials within the slab. As the segment's core is hollow, the likelihood of significant thermal and moisture differentials developing within the precast segment is low, thereby reducing the likelihood of shrinkage cracks.

The Professional Engineers (PE) responsible for design and supervision of the precast box girder segments have assessed the use of carbon mineralised concrete based on the initial validation testing and were of the view that carbon mineralised concrete is unlikely to have implications on the integrity of the concrete structure, be it in the short-term or long-term.

While there are some uncertainties in the use of carbon mineralised concrete thus far, with proper site monitoring and effort, we believe that there is no serious concern in the implementation of carbon mineralised concrete for large-scale infrastructure.

4.2 Cube strength and slump of actual precast box girder segments

Moving on to the actual segment production, a total of 40 box girder segments were casted between 20 Dec 2023 and 29 May 2024. The average value and standard deviation of the slump test and concrete strength at various testing ages is presented in Table 3 below. Details of the individual cube test results and slump tests results are attached in Appendix A.

Table 3 Slump and Cube strength readings over 40 samples.

Segment No.	Average Slump (mm)	Average Compressive Strength (MPa)			
		12 hours	3 days	7 days	28 days
Average	239.5	36.7	55.3	63.9	74.5
Standard Deviation	3.9	2.4	3.0	3.1	2.9

The results indicated that the carbon mineralised concrete performed quite satisfactorily during real-world testing, with compressive strengths of 74.5 MPa on average and standard deviation of 2.9 MPa at 28 days.

Considering that the mix is designed for a cube strength of 55 MPa, we can do a t-test with all 40 28-day samples to determine if less than 5% of samples do not meet the required compressive strength of 55 MPa.

The t-value is given by the formula:

$$t = \frac{\bar{x} - \mu}{s/\sqrt{n}} \quad (1)$$

For our concrete cube test at 28-days, we have number of samples n = 40, expected compressive strength μ = 55, average compressive strength from testing $\bar{x}$ = 74.5, and standard deviation from testing σ = 2.9. At 5% level of significance, a t-value of more than 1.685 (degrees of freedom = 39) would be sufficient to reject the hypothesis that the sample strength does not meet the required compressive strength.

As our t-value is 42.5, we can be quite assured the samples would be able to attain the required compressive strength of 55 MPa at 28-day with less than 5% of samples not meeting the required strength, which is the Professional Engineer's design requirement.

Repeating the same process for the 12-hour cube strength, with number of samples n = 40, expected compressive strength μ = 15, average compressive strength from testing $\bar{x}$ = 36.7, and s = 2.4. This gives us a t-value of 57.2. At 5% level of significance, a t-value of more than 1.685 (degrees of freedom = 39) would be sufficient to reject the hypothesis that the sample strength does not meet the required compressive strength of 15 MPa. Thus, we can be quite assured that the use of carbon mineralised concrete would not affect de-moulding at 12 hours.

The slump of the concrete is satisfactory and within the Professional Engineer's design range of 230 to 250 mm.

4.3 Compressive strength development curve

The strength development curve of the carbon mineralised concrete from site testing is satisfactory. The compressive strength results from testing of concrete used to cast the precast segments on site (blue), compared to cubes of normal concrete EN8663 (red) and carbon mineralised concrete CEN8613 (green) tested as part of the validation testing process described in Section 3.1 above, is shown in Figure 4 below.

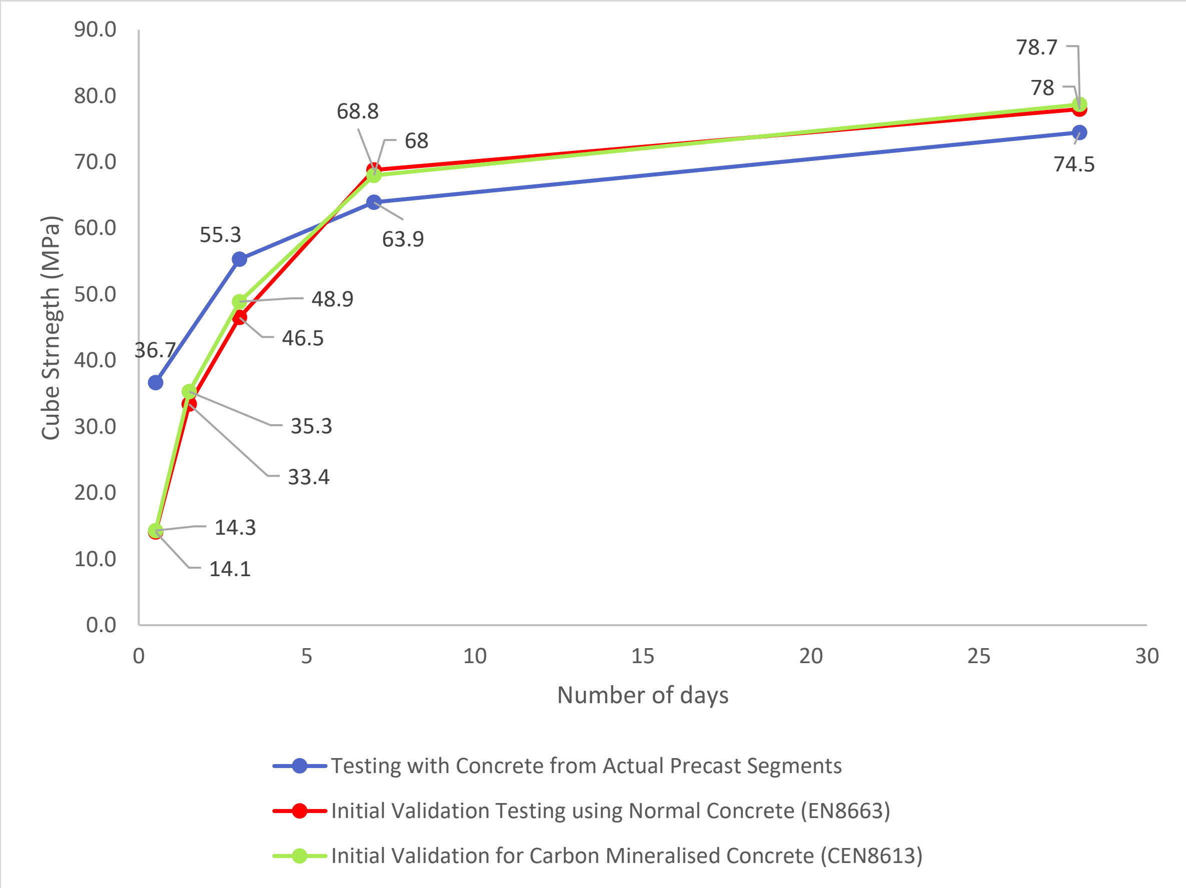

Figure 4 Strength development curve for carbon mineralised concrete and normal concrete tested in lab during validation testing, and actual carbon mineralised concrete samples.

It is noted that during site testing, the test cube attains a higher initial compressive strength (36.7 MPa compared to 14.1 MPa in the lab), but lower 28-day compressive strength (74.5 MPa compared to 78.0 MPa in the lab). It is theorised that the cube samples from the concrete used to cast the actual segments would be exposed to higher temperatures (approx. 33°C on site) during curing on site. The concrete cube sample would thus hydrate more rapidly in the early stages of concrete curing, leading to a higher rate of CSH gel formation and higher initial strength. Whereas for the validation testing samples, the hydration would be slower as the lab temperature is controlled at 25°C, as required under BS EN 12390-3.

With a higher rate of concrete hydration in the earlier stages on site, the calcium silicates would be depleted in the longer term. This means that strength development would become limited later. Thus, there is a limit to the real-world compressive strength development at 28-day compared to the validation testing samples, which had more favourable conditions for long term hydration.

The intention of validation testing in the lab is to facilitate apple-to-apple comparison of results, thus, the conditions have to be controlled, and are usually more favourable for concrete hydration. However, the compressive strength recorded from site testing is of greater importance since this represents the actual conditions in which the segments are being cured, and therefore the actual strength of the precast segments which is crucial for the structural integrity of the viaduct.

Statistical analysis of the compressive cube strengths has provided sufficient confidence that the 28-day strength would meet the design requirements set out. A further benefit is that the higher initial strength on site facilitates precast production work by allowing for early de-moulding of the segments, which allows the moulds to be reused faster for casting the subsequent precast segment.

4.4 Observations post-casting

During casting of the first 40 precast box girder segments, it was observed that the segments casted using carbon mineralised concrete were generally satisfactory. Minor honeycombing and poor compaction were observed during initial casting but were resolved after optimisation of the casting and vibration sequence without any change to the carbon mineralised concrete mix. The team did not observe any phenomenon relating to the higher concrete shrinkage observed in the lab, or any phenomenon relating to the concrete mix that would have propagated to all segments casted using carbon mineralised concrete.

Similar to the casting of precast segments using normal concrete, proper temperature control, installation of reinforcement bar, vibration and curing is crucial to the application of carbon mineralised concrete for precast segments. Pictures of the casted segments are shown below in Figures 5a and 5b.

Figure 5a Picture of casted segment in satisfactory condition.

Figure 5b Picture of casted segments in satisfactory condition.

5. DISCUSSION

5.1 Environmental benefit of using carbon mineralised concrete

In our project, based on the expected concrete volume of 107,400 m^3 for the precast box girder segments, a saving of 20 kg of OPC for each m^3 of carbon mineralised concrete produced would save about 2148 thousand tons of cement. Literature has reported that each ton of OPC generated roughly 0.73 to 0.94 tons of carbon dioxide emissions (He, Zhu, Wang, Wu, & Wang, 2019), (Karadumpa & Pancharathi, 2024). Taking an average emission of 0.8 tons of carbon dioxide for each ton of cement produced, we determine that we can reduce 1718.4 thousand tons of carbon emissions by using carbon mineralised concrete. This is equivalent to the carbon emissions from 365,000 people for an entire year (World average carbon emission per person is 4.7 tons (Global Carbon Budget, 2023)).

There is also a further reduction in emissions stemming from the injection of carbon dioxide to produce carbon mineralised concrete. This reduction in carbon emissions is about 81.6 tons, which is insignificant compared to the emission savings from the reduction in cement content.

5.2 Cost of implementation

To implement the use of carbon mineralised concrete, special equipment is only required at the batching plant, thus any cost differential would be reflected in the cost from the concrete supplier. Raw material costs vary widely across Asia due to availability of sand, coarse aggregate, clinker for production, as well as transportation fees, thus the cost estimate could vary quite significantly. For our project, the supplier has indicated a cost differential of around 1 to 5% (depending on the concrete grade and raw materials used). We also note that the supplier is trying to establish demand for carbon mineralised concrete, and the mark-up may not be adequately reflected in the current pricing. We advise interested parties to consult your respective suppliers if they offer carbon mineralised concrete.

5.3 Further research

One possible area for further research would be the effects of high shrinkage on the segment integrity and geometry, which would become apparent when the precast box girder segments are launched. The effects of high shrinkage may also become more pronounced as the time interval between segment casting and launching becomes shorter with the ramping up of works. This would need to be monitored closely to prevent issues such as early-age cracking which may lead to structural integrity issues, and dimensional instability, which could affect the geometric control of the overall viaduct.

As carbon mineralised concrete is still in its infancy in terms of application to large-scale infrastructure, with the first carbon mineralised concrete building completed less than 10 years ago, there is much room for further study. For instance, carbon mineralised concrete may present improved durability and lower creep in the long-term, which can only be investigated in the many years to come.

Further study on the natural mineralisation of carbon mineralised concrete compared to normal concrete would also be useful to establish the eventual carbon capturing ability of carbon mineralised concrete in the real-world.

6. CONCLUSION

This paper has briefly discussed Singapore's journey in implementing carbon mineralised concrete for precast box girder segments, from initial trial mix testing, to casting of the actual segments and the testing of the cube samples at various ages (12 hours, 3 days, 7 days, 28 days).

The trial mix did not present any significant differences in physical and mechanical properties compared to normal concrete of similar grade, and the required compressive strength (55 MPa at 28 days) was achievable based on actual curing conditions on site. We are able to conclude that there are no significant issues in the adoption of carbon mineralised concrete once there is a proper trial mix formulated and testing regime in place, coupled with good workmanship by the contractor.

In addition, the paper has provided an estimate of the carbon savings and environmental impact achievable in adopting carbon mineralised concrete, as well as lay the foundation for further research. The authors are hopeful that carbon mineralised concrete would be adopted in more projects as part of a renewed global commitment towards environmental sustainability.

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North-South Corridor project. Their dare-to-try spirit has provided valuable inputs on the use of carbon mineralised concrete for casting of precast box girder segments.

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Appendix A. Table of compressive strength and slump values

Table A1 Slump and Cube strength readings.

Segment No.	Average Slump (mm)	Average Compressive Strength (MPa) (s.d.= Standard deviation)			
		12 hours	3 days	7 days	28 days
1	242	29.2 (s.d.= 4.7)	48.3 (s.d.= 6.5)	65.0 (s.d.= 10.7)	72.4 (s.d.= 10.2)
2	231	19.0 (s.d.= 4.0)	41.5 (s.d.= 9.0)	46.2 (s.d.= 8.3)	59.2 (s.d.= 3.5)
3	229	19.8 (s.d.= 0.9)	39.3 (s.d.= 5.0)	54.9 (s.d.= 5.0)	65.0 (s.d.= 6.4)
4	230	25.2 (s.d.= 0.6)	42.3 (s.d.= 1.2)	53.7 (s.d.= 4.6)	64.4 (s.d.= 1.0)
5	245	19.3 (s.d.= 4.6)	37.4 (s.d.= 9.4)	49.1 (s.d.= 12.0)	64.1 (s.d.= 7.8)
6	240	36.9 (s.d.= 0.9)	62.4 (s.d.= 3.5)	70.1 (s.d.= 3.2)	81.1 (s.d.= 5.5)
7	242	18.0 (s.d.= 1.8)	47.0 (s.d.= 4.7)	54.3 (s.d.= 4.9)	71.2 (s.d.= 1.0)
8	240	24.5 (s.d.= 1.4)	52.4 (s.d.= 2.6)	59.7 (s.d.= 2.4)	70.9 (s.d.= 5.9)
9	242	35.9 (s.d.= 4.7)	43.4 (s.d.= 3.2)	54.2 (s.d.= 4.2)	61.9 (s.d.= 5.7)
10	234	26.9 (s.d.= 0.8)	49.2 (s.d.= 2.6)	57.8 (s.d.= 4.7)	69.1 (s.d.= 3.5)
11	238	31.4 (s.d.= 5.1)	63.1 (s.d.= 9.1)	72.2 (s.d.= 8.5)	78.6 (s.d.= 9.2)
12	242	28.9 (s.d.= 8.3)	52.5 (s.d.= 12.8)	62.1 (s.d.= 8.8)	68.1 (s.d.= 7.5)
13	241	47.1 (s.d.= 5.1)	55.9 (s.d.= 6.3)	60.0 (s.d.= 5.2)	63.1 (s.d.= 6.8)
14	241	30.8 (s.d.= 3.3)	52.0 (s.d.= 1.2)	63.4 (s.d.= 5.3)	74.9 (s.d.= 7.8)
15	243	30.0 (s.d.= 8.6)	38.0 (s.d.= 10.9)	50.0 (s.d.= 13.3)	63.9 (s.d.= 7.8)
16	236	19.2 (s.d.= 1.2)	40.0 (s.d.= 8.9)	55.4 (s.d.= 10.5)	66.4 (s.d.= 6.3)
17	235	19.3 (s.d.= 2.0)	32.4 (s.d.= 4.9)	47.5 (s.d.= 0.6)	61.3 (s.d.= 1.7)
18	242	16.1 (s.d.= 0.1)	30.0 (s.d.= 1.7)	43.8 (s.d.= 2.0)	59.6 (s.d.= 2.1)
19	236	19.0 (s.d.= 1.3)	30.4 (s.d.= 7.3)	45.3 (s.d.= 8.7)	62.9 (s.d.=6.7)
20	242	17.4 (s.d.= 2.5)	29.9 (s.d.= 6.1)	39.8 (s.d.= 7.3)	61.1 (s.d.=5.1)
21	242	17.6 (s.d.= 1.5)	30.1 (s.d.= 1.7)	43.1 (s.d.= 3.7)	56.9 (s.d.=1.1)

22	238	40.4 (s.d.= 8.9)	45.1 (s.d.= 11.7)	53.1 (s.d.= 10.9)	60.4 (s.d.=5.7)
23	241	50.3 (s.d.= 2.1)	62.0 (s.d.= 6.0)	65.3 (s.d.= 5.6)	74.9 (s.d.=4.4)
24	240	42.7 (s.d.= 4.1)	57.3 (s.d.= 3.3)	61.4 (s.d.= 4.7)	71.8 (s.d.=1.9)
25	240	56.4 (s.d.= 4.7)	64.6 (s.d.= 3.6)	76.2 (s.d.= 4.1)	80.5 (s.d.=11.1)
26	238	54.0 (s.d. =2.0)	64.7 (s.d. =1.9)	69.7 (s.d. =3.4)	75.3 (s.d. =7.4)
27	240	48.1 (s.d.=1.8)	65.9 (s.d.=5.1)	75.8 (s.d.=3.9)	90.6 (s.d.=5.4)
28	236	39.9 (s.d. =2.2)	75.5 (s.d. =2.3)	87.6 (s.d. =3.6)	100.0 (s.d. =4.2)
29	236	46.8 (s.d.=3.5)	71.6 (s.d.=2.9)	76.1 (s.d.=4.4)	87.3 (s.d.=6.3)
30	244	46.6 (s.d. =0.8)	77.8 (s.d. =4.0)	83.2 (s.d. =3.9)	92.2 (s.d. =12.6)
31	244	50.9 (s.d.=2.8)	67.6 (s.d.=6.5)	73.8 (s.d.=5.6)	85.3 (s.d.=4.5)
32	242	45.7 (s.d. =5.3)	72.6 (s.d. =4.9)	75.2 (s.d. =6.5)	92.4 (s.d. =7.0)
33	243	43.6 (s.d.=2.4)	77.2 (s.d.=5.2)	76.4 (s.d.=7.3)	86.1 (s.d.=8.1)
34	241	52.9 (s.d. =9.6)	73.2 (s.d. =11.0)	74.9 (s.d. =7.2)	87.4 (s.d. =7.0)
35	238	52.3 (s.d.=1.9)	65.5 (s.d.=5.7)	70.9 (s.d.=1.0)	69.3 (s.d.=10.4)
36	243	51.6 (s.d. =5.4)	69.7 (s.d. =4.0)	84.7 (s.d. =1.9)	95.1 (s.d. =2.3)
37	243	50.7 (s.d.=4.9)	77.2 (s.d.=3.1)	79.0 (s.d.=7.8)	83.3 (s.d.=3.0)
38	241	55.8 (s.d. =3.4)	68.5 (s.d. =3.6)	74.6 (s.d. =1.2)	82.4 (s.d. =2.7)
39	241	58.3 (s.d. =6.1)	69.8 (s.d. =6.2)	75.2 (s.d. =3.0)	82.3 (s.d. =3.8)
40	241	49.1 (s.d. =4.2)	70.5 (s.d. =6.7)	75.6 (s.d. =8.5)	87.5 (s.d. =5.4)
Average	239.5	36.7	55.3	63.9	74.5
Standard Deviation	3.9	2.4	3.0	3.1	2.9

Study of Low Carbon Hydraulic Cement in Road Applications

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ABSTRACT

To achieve Thailand's goal of lowering its greenhouse gas emissions (GHGs). Thai cement industry announced a plan to replace clinker to reduce greenhouse gas emissions (GHGs) on the industrial process and product usage. Using hydraulic cement is a suitable substitute for these efforts. This study is Department of Highways (DoH) and Siam City Cement PCL. (INSEE) collaboration project that performances of roadwork materials are compared and examined using Portland cement (Type I) and INSEE hydraulic cement (Type GU). Cementitious materials are used in cement concrete pavement, cement-modified crushed rock base, soil cement base and soil cement column.

To study cement concrete pavement, the Department of Highways (DoH) concrete pavement standards were referred. The cement content of the mixture was limited to 350 kg per cubic meter, the water-to-cement ratio was controlled at 0.50 maximum and water-reducing agents were used to control the initial slump of fresh concrete within 5±2 centimeters. After concrete specimens had cured for 3, 7, 14, and 28 days, tests were conducted to determine its compressive strength. Moreover, the research has tested other concrete properties with the following: shrinkage, abrasion resistance, chloride permeability and the flexural strength of the specimens at 7 and 28 days of curing.

INSEE hydraulic cement (Type GU) and Portland cement (Type I) were used as cementitious materials to stabilize the materials to investigate cement-modified crushed rock base and soil cement base. The maximum dry density was utilized to calculate and control the water content, and cement contents of 2, 3, 4, 5, and 6% were examined to compare the results of the compressive strength tests conducted on specimens aged 7 and 28 days.

The process of studying subgrade involves utilizing INSEE hydraulic cement (Type GU) and Portland cement (Type I) as cementitious materials to improve the soft clay (Bangkok soft clay, Depth 10-20 meters). The cementitious materials were mixed with soft clay samples and the compressive strength was measured after 28 days of curing. The water to cement ratios of 1.0 and 1.2, as well as the cement content applied to 200, 250, and 300 kg per cubic meter of clay, were examined.

Based on the results of all the tests, it can be determined that Portland cement (Type I) and INSEE hydraulic cement (Type GU) can be used as cementitious materials in cement concrete pavement, cement modified crushed rock base, soil cement base, and soil cement column. These materials can be substituted and offer comparable performance and greenhouse gas emissions (GHGs) can also be decreased by using hydraulic cement.

Keywords: Hydraulic cement (Type GU), Portland cement (Type I), Greenhouse Gas Emissions (GHGs)

1. INTRODUCTION

The severity of the climate change issue is growing. Changes in global temperature are caused by an increase in greenhouse gases in the atmosphere. A one-degree increase in global temperature will cause more severe climate change, heavy rainfall, polar ice cap melting, sea level rise, altered ocean current circulation, and perhaps more catastrophic events in the future. The world's temperature has currently increased by 1.2 degrees Celsius due to the growth of greenhouse gasses. The Paris Agreement, which went into effect on September 21, 2016, was the result of negotiations held during the 21st Annual Conference of the Parties (COPs) under the United Nations Framework Convention on Climate Change in 2015. Thailand has established a target to reach net zero emissions by 2065 and to reduce greenhouse gas emissions by 40% from business as usual by 2030. To accomplish this objective, the public and private sectors must work together to drive operations. As such, the Thai cement industry has a difficulty in terms of adaptation. Consequently, Ministry of Natural Resources and Environment, Council of Engineers (COE), Engineering Institute of Thailand (EIT), Thai Cement Industry Association (TCMA), Thailand Concrete Association (TCA), Office of Natural Resources Policy and Planning and Environment (ONEP) and 16 other government agencies have joined forces. On August 31, 2020, MoU was signed pertaining to the integration of cooperation in climate change management with the aim of enabling Thailand to achieve its objective of lowering greenhouse gas emissions on the industrial process and product usage. The goal of the clinker replacement initiative is to reduce carbon dioxide (CO2) emissions by at least 300,000 tons by the year 2022. It is consequently a significant problem that calls for both sustainable environmental care and national growth.

To achieve Thailand's goal of lowering its greenhouse gas emissions (GHGs). Thai cement industry announced a plan to replace clinker to reduce greenhouse gas emissions (GHGs) on the industrial process and product usage. Using hydraulic cement is a suitable substitute for these efforts. This study is Department of Highways (DoH) and Siam City Cement PCL. (INSEE) collaboration project that performances of roadwork materials are compared and examined using Portland cement (Type I) and INSEE hydraulic cement (Type GU). Cementitious materials are used in cement concrete pavement, cement-modified crushed rock base, soil cement base and soil cement column.

2. OBJECTIVE

To study the performance of INSEE hydraulic cement (Type GU) and Portland cement (Type I) in road applications (Cement concrete pavement, Cement modified crushed rock base, Soil cement base and Soil cement column)

3. MATERIAL AND METHODS

3.1 Materials

Table 1 Materials for cement concrete pavement.

Materials	Detail
INSEE hydraulic cement (Type GU)	INSEE Petch Easy Flow
Portland cement (Type I)	INSEE Petch
Fine aggregate	River sand according to ASTM C33
Coarse aggregate	Limestone crushed rock according to ASTM C33 (Normal size 19 mm)
Water	Tap water
Admixture	Water reducing and retarding (Type A&D)

Table 2 Materials for cement modified crushed rock base and soil cement base.

Materials	Detail
INSEE hydraulic cement (Type GU)	INSEE Petch Easy Flow
Portland cement (Type I)	INSEE Petch
Limestone crushed rock	Nakhon Sawan province
Soil	Roi Et province
Water	Tap water

Table 3 Materials for soil cement column.

Materials	Detail
INSEE hydraulic cement (Type GU)	INSEE Petch Easy Flow
Portland cement (Type I)	INSEE Petch
Soft clay	Chatuchak district, Bangkok, Depth 10-20 m
Water	Tap water

3.2 Mixed proportion

Table 4 For cement concrete pavement.

Cement type	Cement (kg)	Sand (kg)	Rock ¾' (kg)	Water (L)	Admixture (mL)	Initial slump (cm)
INSEE hydraulic cement (Type GU)	350	825	1080	175	1600	5
Portland cement (Type I)	350	825	1080	175	1600	5

Table 5 For cement modified crushed rock base and soil cement base.

Materials	Varied cement content (%)	Optimum moisture content (%)	Cement type
Crushed rock	2, 3 and 4%	5.8	INSEE hydraulic cement (Type GU)
			Portland cement (Type I)
Soil	2, 3, 4, 5 and 6%	9.6	INSEE hydraulic cement (Type GU)
			Portland cement (Type I)

Table 6 For soil cement column.

W/C ratio	Cement content (kg/m3)	Cement type
1.0	200, 250 and 300	INSEE hydraulic cement (Type GU)
		Portland cement (Type I)
1.2	200, 250 and 300	INSEE hydraulic cement (Type GU)
		Portland cement (Type I)

3.3 Methods

- Cement concrete pavement

Department of Highways (DoH) concrete pavement standards were referred (DH-S 309/2001). The cement content of the mixture was limited to 350 kg per cubic meter, the water-to-cement ratio was controlled at 0.55 maximum and water-reducing agents were used to control the initial slump of fresh concrete within 5±2 centimeters. After concrete specimens had cured for 3, 7, 14, and 28 days, tests were conducted to determine its compressive strength. Moreover, the research has tested other concrete properties with the following: Total shrinkage, abrasion resistance, chloride permeability and the flexural strength of the specimens at 7 and 28 days of curing.

Table 7 Test methods and condition

Laboratory tests	Standard test methods	Age of test/Condition
Slump	ASTM C143	Initial
Setting time	ASTM C403	Stiffening/Initial/Final
Compressive strength	AASHTO 22-66/BS 1881 Part 4	3, 7, 14 and 28 days
Flexural strength	AASHTO T97-97	7 and 28 days
Total shrinkage	ASTM C157	0 – 56 days
Abrasion resistance	ASTM C944 (Under loading 20kg)	7, 28 and 56 days
Rapid chloride penetration	ASTM C1202	28 and 56 days

- Cement modified crushed rock base and soil cement base.

INSEE hydraulic cement (Type GU) and Portland cement (Type I) were used as cementitious materials to stabilize the materials to investigate cement-modified crushed rock base and soil cement base. The maximum dry density was utilized to calculate and control the water content (Optimum moisture content, OMC), and cement contents of 2, 3, 4, 5, and 6% were examined to compare the results of the compressive strength tests conducted on specimens aged 7 days.

Table 8 Test methods and condition

Laboratory tests	Standard test methods	Age of test/Condition
Gradation	DH-T 204/1973 / AASHTO T27	-
Liquid limit	DH-T 102/1972 / AASHTO T89	-
Plastic limit	DH-T 103/1972 / AASHTO T90	-
CBR	DH-T 109/1974 / AASHTO T193	95% maximum dry density at 0.1-inch penetration
Compaction test	DH-T 108/1974 / AASHTO T180	Modified proctor
Unconfined compressive strength	DH-T 105/1972 / AASHTO T208	7 days

- Soil cement column

The process of studying subgrade involves utilizing INSEE hydraulic cement (Type GU) and Portland cement (Type I) as cementitious materials to improve the soft clay (Bangkok soft clay, Depth 10-20 meters). The cementitious materials were mixed with soft clay samples and the compressive strength was measured after 28 days of curing. The water to cement ratios of 1.0 and 1.2, as well as the cement content applied to 200, 250, and 300 kg per cubic meter of clay, were examined.

Table 9 Test methods and condition

Laboratory tests	Standard test methods	Age of test/Condition
Liquid limit	AASHTO T89	-
Plastic limit	AASHTO T90	-
S.G. of soil	ASTM D854-92	-
Unconfined compressive strength	ASTM D2166	W/C = 1.0 and 1.2 at 28 days

4. TEST RESULTS

4.1 Cement concrete pavement

- Basic properties of materials

Table 10 Chemical properties of cement

Properties	Portland cement (Type I)	INSEE hydraulic cement (Type GU)
SiO2	19.9	18.7
Al2O3	4.8	4.6
Fe2O3	3.0	2.8
CaO	64.6	62.8
MgO	1.3	1.7
SO3	2.95	3.05
Na2O	0.18	0.20
K2O	0.44	0.44
Na eq.	0.47	0.49
Free-CaO	1.3	1.0
LOI	2.9	4.9
Insoluble residue	0.49	0.56

Table 11 Physical properties of cement

Properties	Portland cement (Type I)	INSEE hydraulic cement (Type GU)
Blaine (m2/kg)	366	414
Residue on 36 µm (%wt)	8.2	7.5
Residue on 45 µm (%wt)	4.3	3.0
Air content (%v)	10.1	9.0
Initial setting time (min)	104	126
Final setting time (min)	165	240
Compressive strength (MPa)		
1 day	16.1	17.4
3 days	29.8	30.3
28 days	42.1	42.0

- Fresh properties of concrete – Setting time

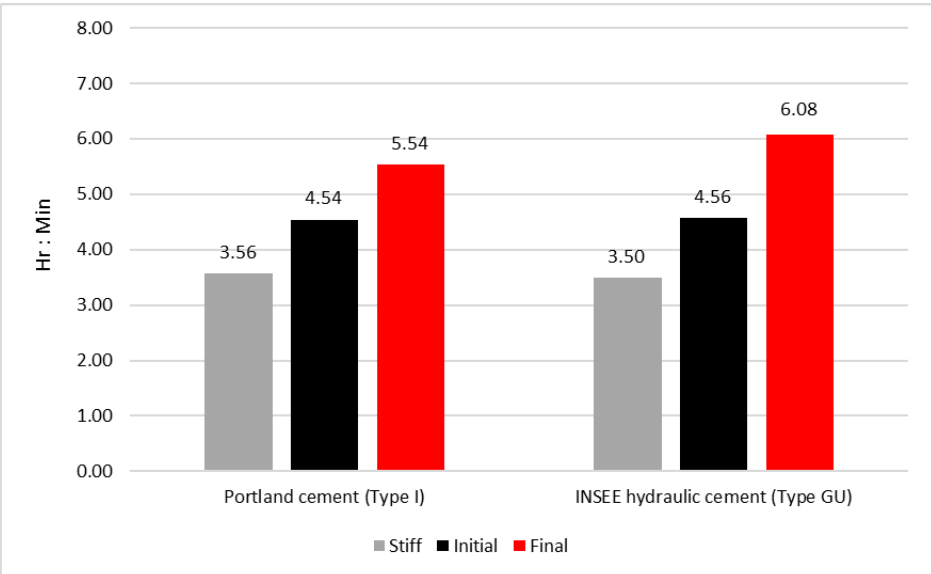

Figure 1 Setting time of concrete

- Harden properties of concrete

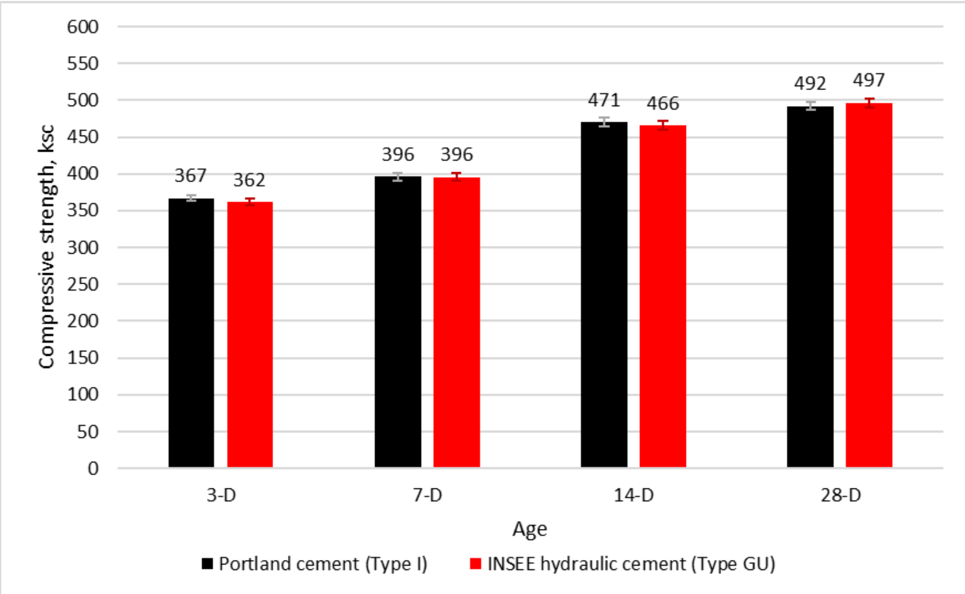

Figure 2 Compressive strength

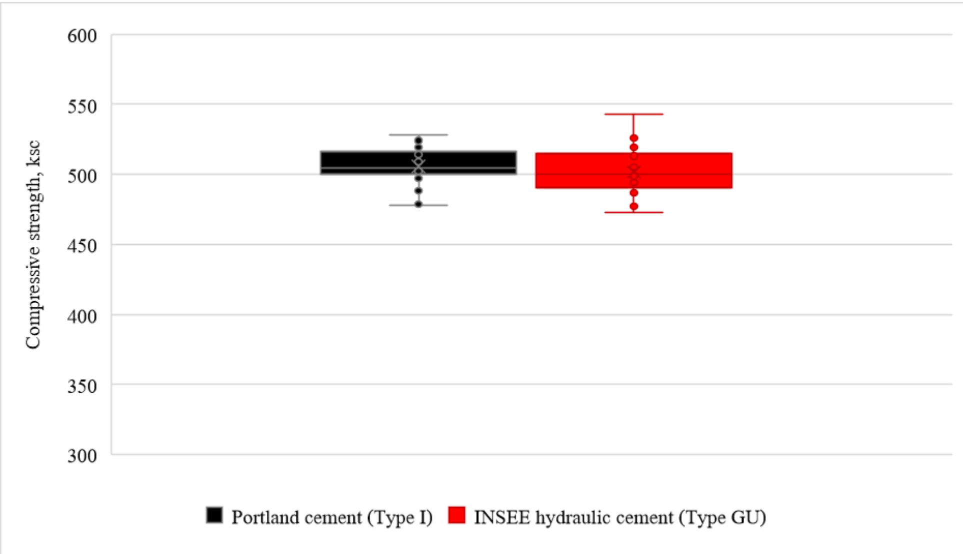

Figure 3 28 days compressive strength – Box plot

Table 12 Statistic analysis – 28 days compressive strength test results

Statistic value	Portland cement (Type I)	INSEE hydraulic cement (Type GU)
Mean	506	502
Maximum	528	543
Minimum	478	473
Standard deviation	13	17
Sample size	30	30
P-value (2 sample T)	0.328	

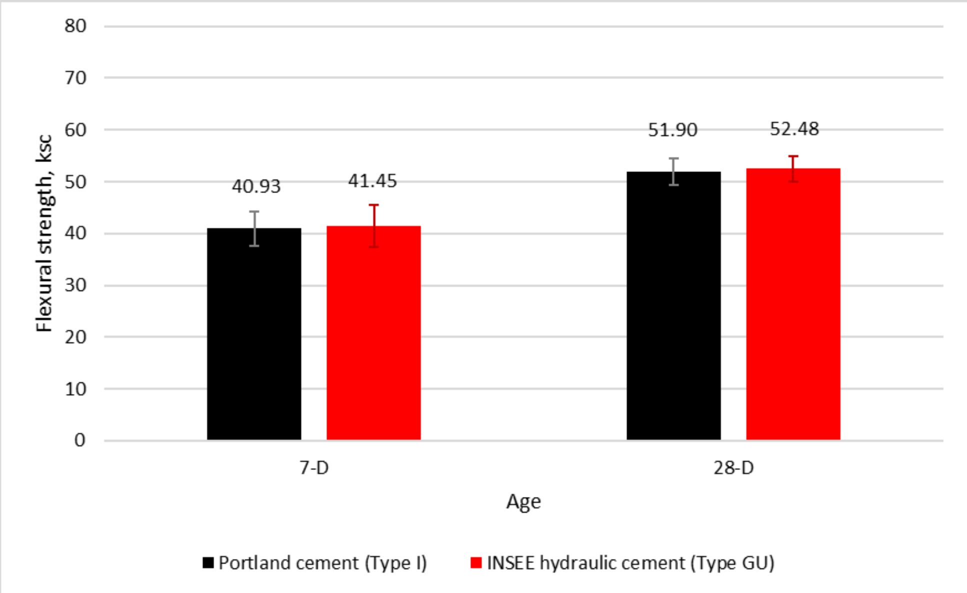

Figure 4 Flexural strength

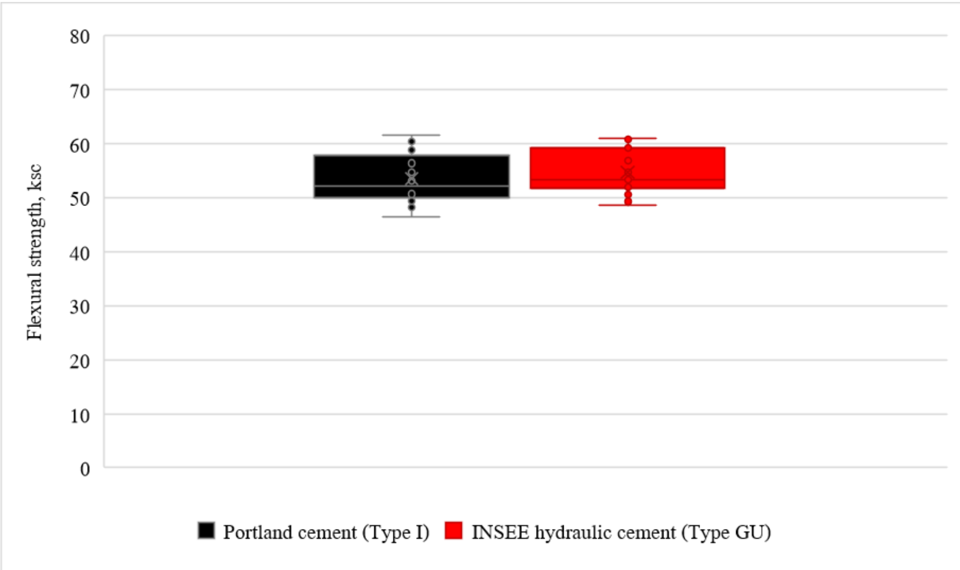

Figure 5 28 days flexural strength – Box plot

Table 13 Statistic analysis – 28 days flexural strength test results

Statistic value	Portland cement (Type I)	INSEE hydraulic cement (Type GU)
Mean	53.41	54.63
Maximum	61.50	61.00
Minimum	46.46	48.50
Standard deviation	4.39	3.92
Sample size	30	30
P-value (2 sample T)	0.263	

Based on similar workability, test findings for compressive strength and flexural strength utilizing different types of cement are comparable. The test results are acceptable according to DoH's specification (DH-S 309/2001) for cement concrete pavement. The P value for both hypothesis test (2 sample T) was greater than 0.05 (Table 12 and 13), indicating that there is no significant difference between the two groups of continuous testing data.

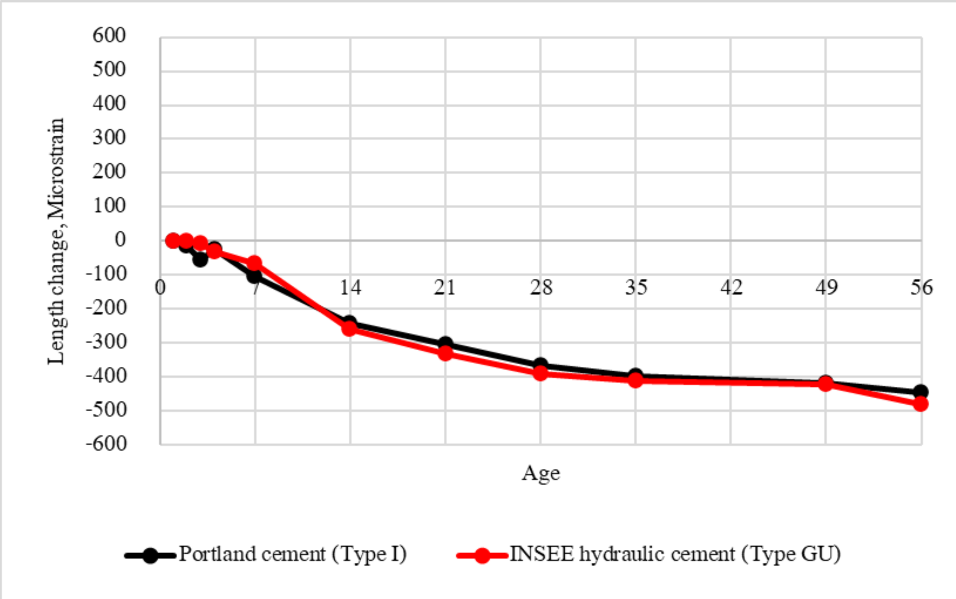

Figure 4 Length change test (Total shrinkage)

It was discovered that the shrinkage values of concrete utilizing Portland cement (Type I) and INSEE hydraulic cement (Type GU) with the same curing condition have similar values based on the average of the test results. The total shrinkage values in the test findings at 56 days of curing were 445 and 480 micro-strains respectively.

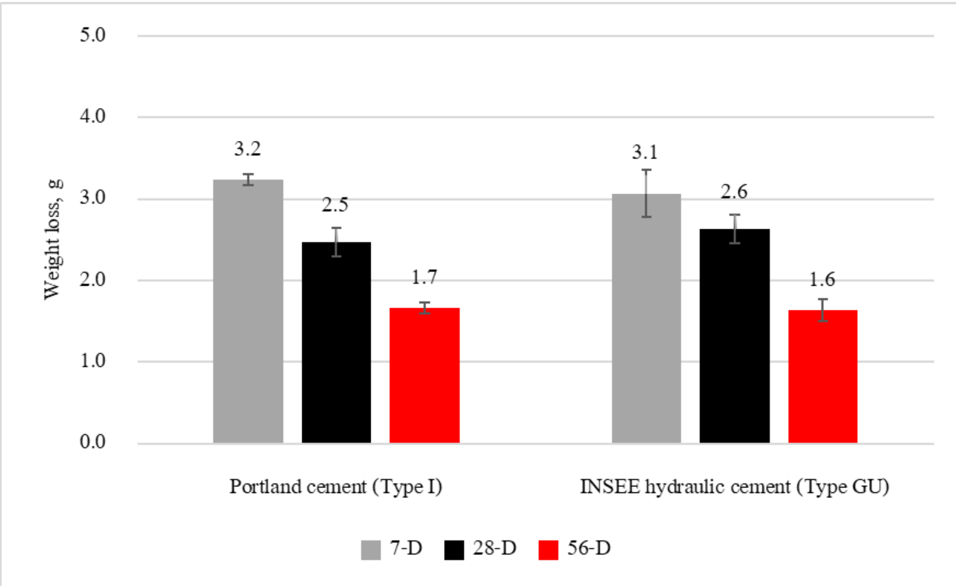

Figure 5 Abrasion resistance

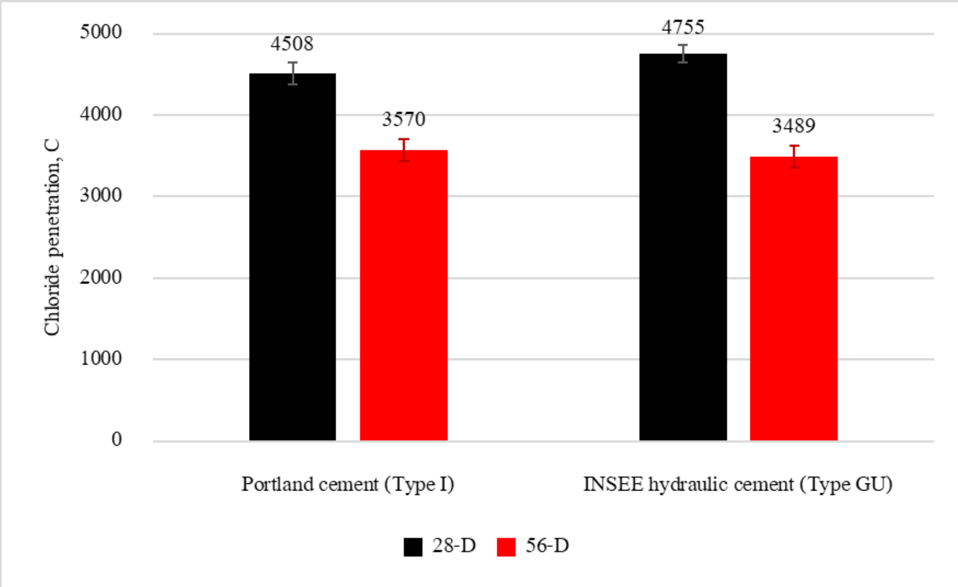

Figure 6 Rapid chloride penetration

The test findings show that the other durability of the concrete specimens, such as their resistance to abrasion and chloride penetration, is comparable when Portland cement (Type I) and INSEE hydraulic cement (Type GU) are used.

4.2 Cement modified crushed rock base and soil cement base.

- Basic properties of materials

Table 14 Basic properties of materials

Properties	**Materials**	
	Crushed rock	**Soil**
Maximum dry density (g/cm3)	2.286	2.116
Optimum moisture content (%)	5.8	9.6
Liquid limit (%)	Non-plastic	27.7
Plastic index (%)	Non-plastic	7.0
CBR at 95% maximum dry density (%)	82.4	-

- Unconfined compressive strength of cement modified crushed rock base – 7 days.

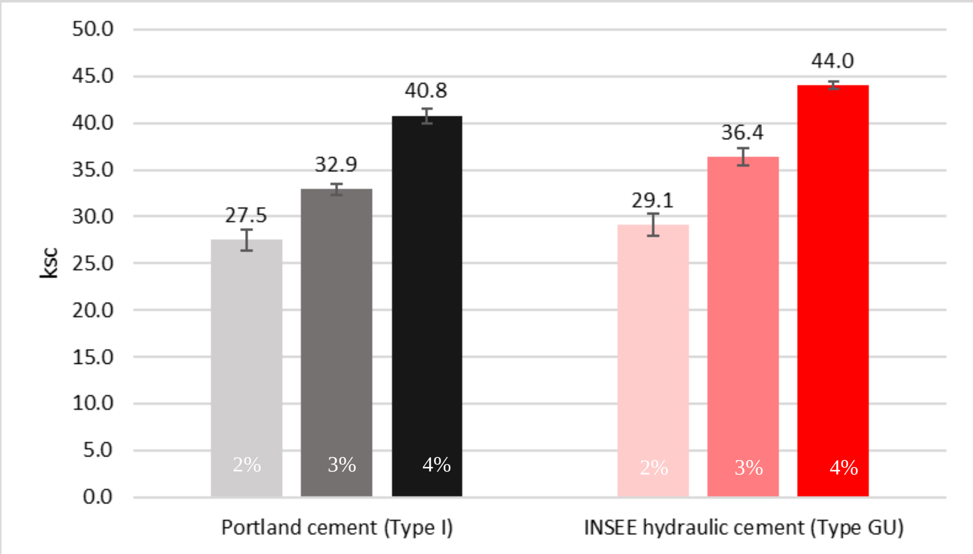

Figure 7 Unconfined compressive strength test results of cement modified crushed rock base – 7 days.

Following treatment of crushed rock samples with different types of cement, the unconfined compressive strength exhibited an increasing trend as cement content increased, indicating an impact on the cement-water hydration reaction. Around 2% cement content could be achieved 7 days target strength for basement application (DH-S 203/2001: Cement modified crushed rock base requires 7 days strength ≥24.5 ksc).

- Unconfined compressive strength of soil cement base – 7 days.

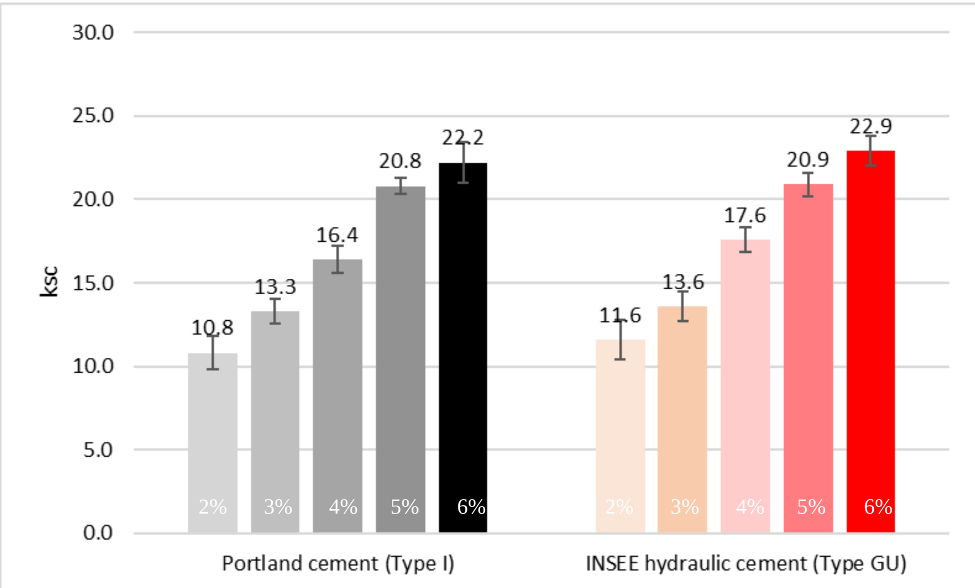

Figure 8 Unconfined compressive strength test results of soil cement base – 7 days.

Following treatment of soil samples with different types of cement, the unconfined compressive strength exhibited an increasing trend as cement content increased, indicating an impact on the cement-water hydration reaction. Around 4 -5% cement content could be achieved 7 days target strength (DH-S 204/2013: Soil cement base requires 7 days strength ≥17.5 ksc).

4.3 Soil cement column

- Basic properties of materials

Table 15 Basic properties of materials

Laboratory tests	Test results of soil
Natural water content (%)	64.09
Liquid limit (%)	59
Plastic limit (%)	17
Plastic index	42
Liquid index	1.32
S.G. of soil	2.68
Unit weight of soil (g/cm3)	1.56

- Unconfined compressive strength – 28 days

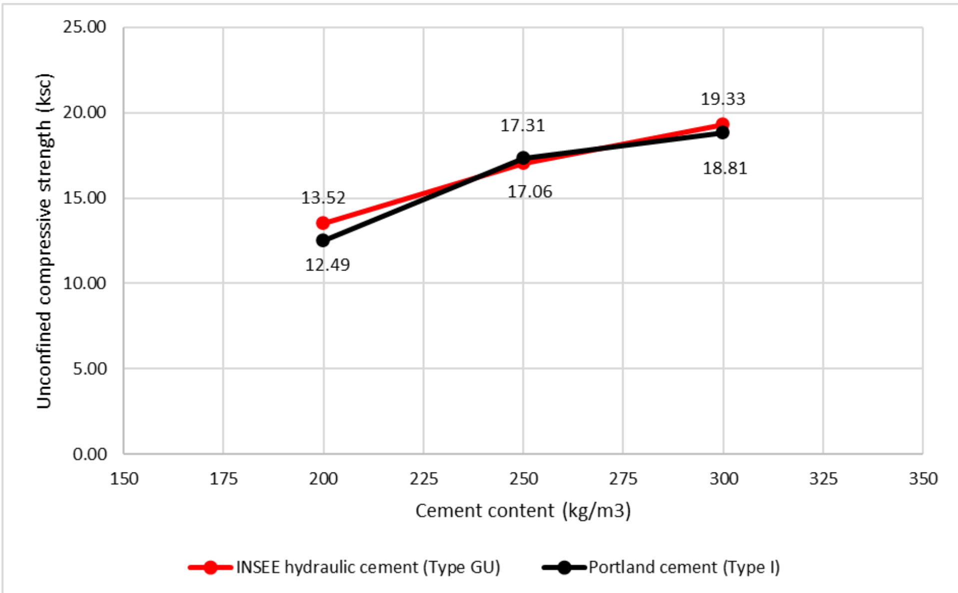

Figure 9 Unconfined compressive strength test results at 28 days – W/C 1.0

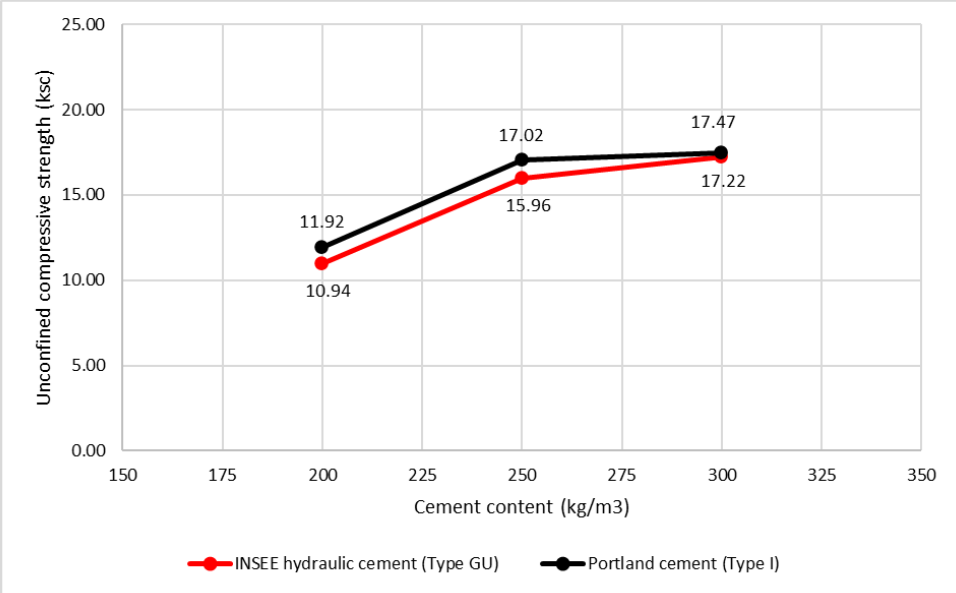

Figure 10 Unconfined compressive strength test results at 28 days – W/C 1.2

Following treatment of soil samples with different types of cement, the unconfined compressive strength exhibited an increasing trend as cement content increased, indicating an impact on the cement-water hydration reaction. Around 200 kg cement per cubic meter of soil could be achieved 28 days target strength (Local project reference specification ≥10.0 ksc) with lower W/C ratio showed greater than the performance.

5. CONCLUSIONS

Based on the results of all the tests, it can be determined that Portland cement (Type I) and INSEE hydraulic cement (Type GU) can be used as cementitious materials in cement concrete pavement, cement modified crushed rock base, soil cement base, and soil cement column. These materials can be substituted and offer comparable performance and greenhouse gas emissions (GHGs) can also be decreased by using hydraulic cement.

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Ms. Mayuree Ratchatarungrodkul (SCCC)	Advisor
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Mr. Worawuth Talubnak (SCCC)	Technician

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Real-World Insights into Carbon Emissions: Pioneering Green Logistics in Cold Chain Transportation

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ABSTRACT

Sustainable urban development necessitates low-carbon transportation, especially in the cold chain logistics sector where transporting perishable goods generates significant emissions due to fuel-intensive refrigeration. Addressing the lack of empirical research, our study uses real-world data from 73 long-haul trips by a logistics company to create a detailed carbon emission model. This model segments emissions across operational phases: 85.9% from transportation, 11.2% from unloading, and 2.9% from loading, analyzing factors like driving, refrigeration processes, and refrigerant leakage. The findings reveal that transportation emissions are mostly from driving (94.4%), unloading emissions from door operations (39.6%), and loading emissions predominantly from pre-cooling (43.3%). The study also identifies significant temperature-dependent fluctuations in refrigeration emissions—up to 4.5 times with changes from 11 to 29 degrees Celsius. The model's precision is demonstrated by a low 0.72% error rate when comparing calculated to actual fuel use. This research advances green logistics and supports the transition to a net-zero future by pinpointing major emission sources and guiding decarbonization efforts, including investigating the impacts of different vehicle sizes and refrigeration settings. We are also exploring additional strategies like electrifying transport refrigeration units (TRUs) to further reduce emissions. These initiatives contribute to enhancing transportation system resilience and sustainability, aligning with global efforts to fortify road networks against environmental challenges and climate change impacts.

Keywords: Cold Chain Logistics, Fresh Goods Transport, Carbon Footprint Modeling, Refrigeration Impact Analysis, Data-Driven Logistics Study

1. INTRODUCTION

The 2015 Paris Agreement established a framework for sustained climate action, aiming to limit global warming to below 2°C above pre-industrial levels, with efforts to further limit it to 1.5°C (UNFCCC, 2020). To achieve this long-term goal, all countries, especially the largest emitters, are committed to fulfilling their national climate pledges. The transportation sector accounts for 24% of carbon emissions (Ritchie & Roser, 2023), particularly with cold chain logistics necessitating the use of diverse refrigeration equipment to meet their specific temperature requirements, resulting in substantial emissions (Bin et al., 2022). Cold chain logistics contribute approximately 4% of total global carbon emissions (UNEP & FAO, 2022), primarily stemming from fuel consumption by vehicle and refrigeration system engines, as well as refrigerant leakage (Bin et al., 2022; Carlsson-Kanyama, 1998; Gloël et al., 2022; Tassou et al., 2009; Wu et al., 2022). This highlights the critical importance of decarbonizing cold chain transportation to achieve global net-zero targets.

Refrigerated vehicles used for transporting fresh goods are typically equipped with temperature control devices known as transport refrigeration units (TRUs), which are usually powered by the vehicle's diesel engine. Several studies have evaluated the environmental impact of these vehicles. Wu et al. (2022) proposed a carbon footprint model for refrigerated vehicles based on Life Cycle Assessment (LCA). The results indicated that the carbon footprint of refrigerated vehicles during the usage phase accounts for approximately 96% of the total carbon emissions. Obviously, the increased fuel consumption and carbon emissions during this phase are primarily due to the additional weight and frontal area of the TRU, as well as the diesel engine's role in powering the TRU. Yang et al. (2021) utilized the instantaneous vehicle emission model, PHEM (the Passenger car and Heavy duty Emission Model), to determine that vehicles equipped with TRUs emit 15% more CO2 and are estimated to increase NOX emissions by 18% compared to standard trucks. The increase in carbon emissions from refrigerated vehicles can also be attributed to various external factors, including the temperature of the refrigerated room and ambient conditions (Adekomaya et al., 2016; Rai, 2019; Rai & Tassou, 2017; Yang et al., 2021), the risk of refrigerant leakage (Gloël et al., 2022; Tassou et al., 2009; Wu et al., 2013), the duration of door openings by operators (Rai, 2019; Yang et al., 2021), and driver behavior (Demir et al., 2011; Yang et al., 2021). Furthermore, refrigerated vehicles still primarily rely on traditional fuel sources (Rai, 2019; Rai & Tassou, 2017), which also contributes to their higher carbon emissions.

Existing research on the calculation of carbon emissions in logistics transportation primarily focuses on computing carbon emissions throughout the lifecycle of fresh goods (Bin et al., 2022; Carlsson-Kanyama, 1998; Shen et al., 2023) or developing optimization models for cold chain logistics routes that consider emissions (Chen et al., 2021; Liu et al., 2019; Qin et al., 2019). While there are established models for estimating carbon emissions from transportation based on fuel consumption or energy use, there has been limited attention to utilizing real-world and real-time data for analyzing carbon emissions at different operational phases of cold chain logistics from a detailed, micro perspective. This gap is largely attributed to the scarcity of relevant data. With the recent advancements in Internet of Things (IoT) technology, which facilitate the capture of real-world and real-time data, a pivotal shift towards green logistics is expected (Liu et al., 2019). It is anticipated that companies will increasingly adopt data-driven strategies to enhance efficiency and sustainability within their logistics systems. Building on this technological progression, this study utilizes a logistics company in Taiwan as a case study to quantify carbon emissions at each operational stage of cold chain logistics transport. This will be achieved by leveraging the company's IoT data within a detailed, bottom-up carbon emission model developed specifically for this purpose. Additionally, the study investigates the impact of environmental temperature on the performance of TRUs, offering a comprehensive understanding of their role in cold chain logistics and the potential for emissions reduction.

2. MATERIAL AND METHODS

2.1 Material

To effectively understand the logistics transportation process of the case company in Taiwan, it is crucial to detail the typical journey involved in cold chain operations. As illustrated in Figure 1, the logistics transportation process begins at a depot where the TRU of a refrigerated truck is activated and the cargo loaded. The vehicle then proceeds to make multiple delivery stops, offloading portions of the cargo at each location. After all deliveries are completed, the TRU is turned off, and the empty vehicle returns to the depot.

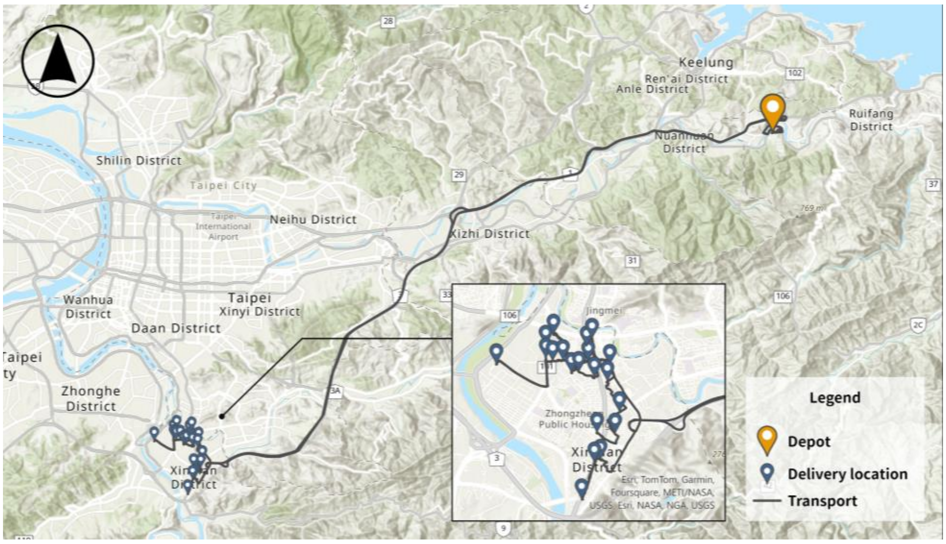

Figure 1 Route of a typical logistics transportation trip for cold chain operations at the case company in Taiwan, showing the depot, delivery locations, and transport paths.

The company's fleet consists of EURO 6 refrigerated trucks (Figure 2). These 3.36-ton gross vehicles, with cargo weights up to 1.64 tons, are maintained at a target temperature of 18 degrees Celsius. Additionally, they are equipped with advanced tracking technologies, including second-by-second GPS tracking, cargo temperature sensors, and geofencing capabilities. These features allow for the capture of detailed data on the refrigerated trucks' status and operational phases every second. Sensor data also includes fuel tank information, which is used for subsequent verification of fuel consumption in carbon emission models.

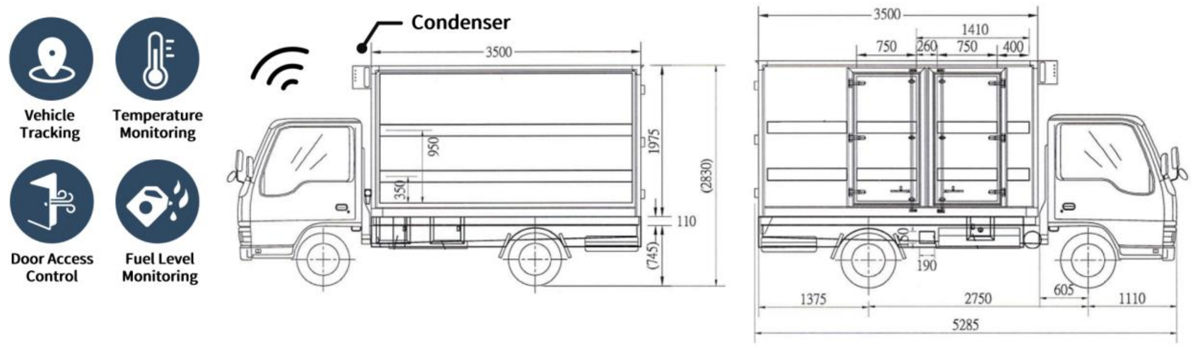

Figure 2 Dimensions of the company's refrigerated truck in centimeters.

Figure 3 presents a time series analysis of telematics data collected via sensors installed by the logistics company. It illustrates the dynamic interplay among vehicle speed (km/h), cargo temperature (°C), and fuel tank diesel level (liters) over time, serving as an example of the data used in this study to demonstrate operational patterns and inform our analysis. For example, the chart shows the vehicle starting and being refueled around 6 a.m., which corresponds with the commencement of the pre-cooling process. Subsequently, the internal temperature drops from the overnight residual heat of 21.18°C to the desired set point, signaling the start of the loading phase. Throughout the journey, the cargo compartment temperature is maintained within the set range, although it experiences fluctuations due to external factors like door openings during delivery stops.

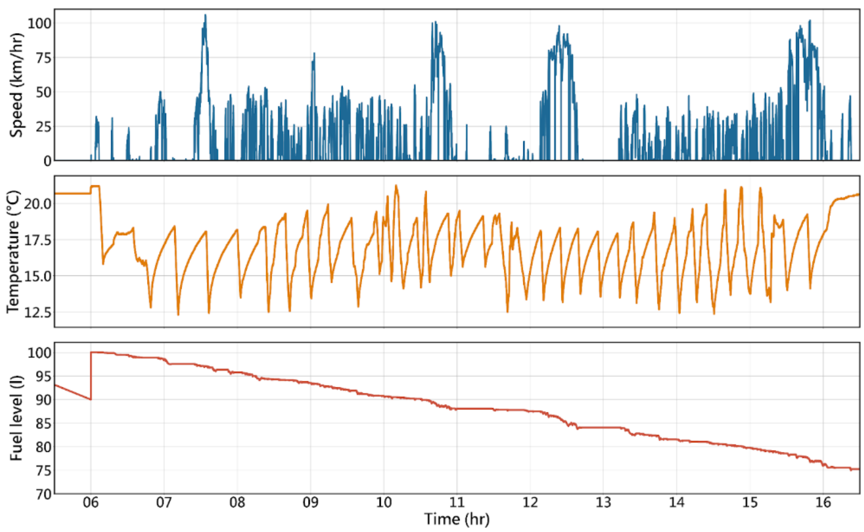

Figure 3 Time series analysis displaying variations in vehicle speed, cargo temperature, and fuel consumption throughout a specific delivery.

Utilizing real-world data from 73 long-haul trips that transported fresh goods to various convenience stores, our study precisely calculates carbon emissions at each stage of the transportation process. The trips involved in this study averaged 4.86 hours in delivery time, covered a travel distance of 78.11 km, and included approximately 23 delivery stops per trip.

2.2 Bottom-up carbon emission model

In this section, we measure the potential global warming effects of different types and amounts of greenhouse gases using carbon dioxide equivalent (CO2e), which reflects the functionally equivalent amount of CO2. For a detailed description of the parameters, please refer to Table 1.

- ***2.2.1 Carbon emissions from driving***

Carbon emissions are closely linked to vehicle fuel consumption, influenced by vehicle-specific factors, environmental conditions, and traffic-related parameters (Demir et al., 2014). To estimate total carbon emissions from vehicle operations, we use the Comprehensive Modal Emission Model (CMEM) developed by Barth et al. (2005). This microscopic model (Equations (1)-(2)), suitable for both heavy-duty diesel vehicles and light-duty trucks, calculates the second-by-second engine power demand ($P_{driving}$ in kW) based on variables such as speed, weight, and slope. It then estimates the instantaneous fuel usage rate ($F_{driving}$ in liters/s). Engine power demand from auxiliary vehicle systems like air conditioning (P_{acc}) is considered negligible according to Demir et al. (2011). Equation (3) converts the estimated fuel consumption into emissions resulting from the combustion process ($Emission_{driving}$ in kg CO2e), utilizing the latest United Kingdom carbon emission conversion factor for diesel, which is 2.66 kg CO2e per liter (DESNZ, 2023).

$$P_{driving} = \frac{0.5C_d\rho A v^3 + (W_v + W_l)v(a + g\sin\theta + gC_r\cos\theta)}{1000\epsilon} + P_{acc} \tag{1}$$

$$F_{driving} = \frac{\xi}{\kappa\psi}\left(kNV + \frac{P_{driving}}{\varpi}\right) \tag{2}$$

$$Emission_{driving} = F_{driving} \times EF_{diesel} \tag{3}$$

- ***2.2.2 Carbon emissions from refrigeration***

The TRU controls the cargo space temperature by removing the thermal load encountered by the refrigerated truck. We employ a refrigeration model based on calculations defined by ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) and enhanced by Bin et al. (2022) (Equations (4)-(8)). The thermal load (Q_{ref} in kWh) considered in this study comprises three main sources: (1) transmission load (Q_{trans}), which refers to the heat transferred into the refrigerated space through its surfaces; (2) precooling load (Q_{pre}), which involves the heat removed from the insulated box and the air inside it; (3) infiltration load (Q_{inf}), which represents the heat gain when doors are opened and external air enters the refrigerated space. The diverse, pre-packaged nature of the transported goods, which are pre-cooled in a cold storage facility, allows us to omit product load from our analysis, as its impact is negligible (Rai, 2019; Rai & Tassou, 2017; Yang et al., 2021). Equations (9) and (10) convert this thermal load into fuel consumption (F_{ref} in liters) and resultant carbon emissions ($Emission_{ref}$ in kg CO2e).

$$Q_{ref} = Q_{trans} + + Q_{pre} + Q_{inf} \tag{4}$$

$$Q_{trans} = \sum U \cdot A \cdot (T_{amb} - T_{int}) \tag{5}$$

$$U = \frac{1}{\sum_{i=1}^{n} \frac{x_i}{k_i}} \tag{6}$$

$$Q_{pre} = \frac{(V_{load} \cdot \rho_a \cdot C_{pa}) \cdot (T_{ini} - T_{set})}{1000} \tag{7}$$

$$Q_{inf} = T \cdot 0.577 \cdot W \cdot H^{1.5} \cdot (\frac{Q_s}{A}) \cdot (\frac{1}{R_s}) \tag{8}$$

$$F_{ref} = \frac{Q_{ref}}{q \cdot \eta \cdot COP_{diesel}} \tag{9}$$

$$Emission_{ref} = F_{ref} \times EF_{diesel} \tag{10}$$

- ***2.2.3 Carbon emissions from refrigerant leakage***

Refrigerant leakage contributes significantly to the global warming potential of refrigeration equipment, accounting for about 20% of its impact (March Consulting Group, 1998). TRUs exhibit higher refrigerant emissions compared to stationary systems due to their operation in more challenging environments, characterized by vibrations from road travel and exposure to diverse weather conditions and temperatures (Tassou et al., 2009). Even new trucks can exhibit initial refrigerant leakage rates of up to 13%, and these rates can increase as the refrigeration equipment ages. Moreover, when refrigeration equipment reaches the end of its service life, any remaining refrigerant is often released into the atmosphere, further exacerbating leakage rates (Gloël et al., 2022). Equation (11) computes the carbon emissions from refrigerant leakage when the TRU is operational ($Emission_{leakage}$ in kg CO2e), based on the type of refrigerant used, the amount of leakage, and the operation time (Wu et al., 2013). The refrigerant R404A, commonly used in refrigerated trucks (Bin et al., 2022), has a GWP of 3922(Rai & Tassou, 2017).

$$Emission_{leakage} = \frac{(R \times \alpha \times GWP)}{L} \tag{11}$$

Table 1 Description of parameters used in model

Parameter	Description	Value	Source
Driving			
W_v	Gross vehicle weight (kg)	3360	Company data
W_l	Payload of vehicle (kg)	NA[a]	Company data
A	Frontal surface area (m^2)	3.762	Company data
V	Engine displacement (liters)	5.193	Company data
v	Speed (m/s)	NA[a]	Sensors
a	Acceleration (m/s^2)	NA[a]	Computing from field
θ	Road gradient (degrees)	NA[a]	Computing from GPS
ξ	Fuel-to-air mass ratio	1	Franceschetti et al. (2013)
κ	Heating value for diesel fuel (kJ/g)	44	
ψ	Conversion factor from grams to liters	737	
k	Engine friction factor	0.2	
N	Engine speed (rev/s)	33	
ρ	Air density (kg/m^3)	1.2041	
C_d	Coefficient of aerodynamic drag	0.7	
C_r	Coefficient of rolling resistance	0.01	
g	Gravitational constant (m/s^2)	9.81	
ϵ	Vehicle drive train efficiency	0.4	
ϖ	Efficiency parameter for diesel engines	0.9	
Refrigeration			
U	Overall heat transfer coefficient (W/(m2 ·K))	0.33	Company data
A	Area of surface (m^2)	41.0502	Company data
T_{amb}	Ambient/external temperature (K)	NA[a]	Central Weather Administration, MOTC
T_{int}	Represents the internal temperature (K)	NA[a]	Sensors
x_i	Thickness of material (m)	0.1	Company data
k_i	Thermal conductivity of the materials (W/(m ·K))	0.033	Company data
V_{load}	Payload volume (m3)	12.27	Company data
ρ_a	Air density ($kg \cdot m^{-3}$)	1.293	
C_{pa}	Specific heat of air ($kJ \cdot kg^{-1} \cdot K^{-1}$)	1.0057	
T_{ini}	Initial temperature inside the body (K)	NA[a]	Sensors
T_{set}	Thermostat setting temperature (K)	NA[a]	Sensors
T	Door opening time (s)	NA[a]	Computing from sensor
W	Doorway width (m)	0.8	Company data
H	Doorway height (m)	1.5	Company data
$\frac{Q_s}{A}$	Sensible heat load of infiltration air per square meter of doorway opening ($kW \cdot m^{-2}$)	4 or 10	ASHRAE 2018
R_s	Sensible heat ratio of the infiltration air heat gain	0.48	ASHRAE 2018
q	Diesel heating value (kJ/l)	35145.6	Energy Administration, MOEA
η	Efficiency of diesel-engine generator	0.4	Bin et al. (2022)
COP_{diesel}	Coefficient of performance of plug-in refrigeration	2.071	Company data
Refrigerant leakage			
R	Refrigerant charge (kg)	1.4	Company data
α	Annual leakage rate (%)	10	Rai and Tassou (2017)
L	Annual operating time (s)	12x22x8x 3600	Inferring from working hours

[a] The parameter is not a single value.

3. RESULTS

3.1 Analysis of carbon emissions by operational phase

We categorize carbon emissions by operational phase into three stages: Transport, Loading, and Unloading. The Loading phase includes the time spent at the depot, the Unloading phase accounts for the time spent at delivery locations, and the Transport phase encompasses the movement between the depot and delivery locations.

Figure 3 shows the average carbon emissions per trip to be 36.29 kg CO2e, distributed as 85.9% from transport, 11.2% from unloading, and 2.9% from loading. The figure further disaggregates emissions by sources, highlighting distinctive emission profiles for each phase. During the Transport phase, emissions are primarily from fuel combustion (94.4%), with smaller contributions from transmission and refrigerant leakage (5.4% and 0.2%, respectively). The Unloading phase sees significant impacts from transmission and door operations, which contribute 58.2% and 39.6% to emissions, respectively, with refrigerant leakage accounting for 2.2%. In the Loading phase, transmission, pre-cooling, and refrigerant leakage contribute 52.9%, 43.3%, and 3.8% of emissions, respectively.

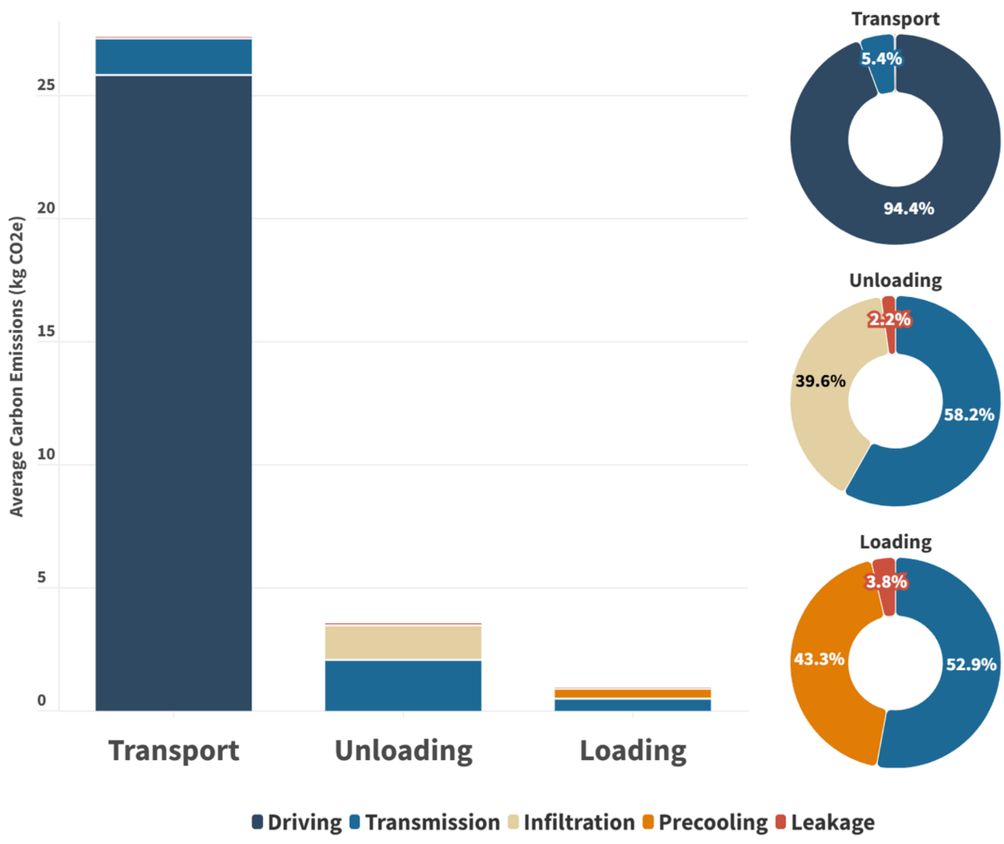

Figure 3 Breakdown of average carbon emissions per operational phase

3.2 Impact analysis of ambient temperature on emissions

Ambient temperature plays a critical role in influencing the carbon emissions of TRUs (Rai & Tassou, 2017; Yang et al., 2021). Our study assesses how ambient temperature impacts emissions from refrigeration and refrigerant leakage. Figure 4 illustrates that an increase in the average ambient temperature during transportation (from 11°C to 29°C) can cause refrigeration carbon emissions to vary by up to 4.5 times, with transmission emissions showing the most substantial fluctuation — varying up to 93 times. This significant difference is due to the smaller temperature differential between the interior and exterior at lower ambient temperatures, which substantially reduces transmission carbon emissions. Conversely, infiltration and precooling emissions are less affected by temperature changes, being primarily dependent on door operation time and the set cargo temperature. Additionally, refrigerant leakage emissions are notably lower in cooler conditions due to decreased air conditioning usage.

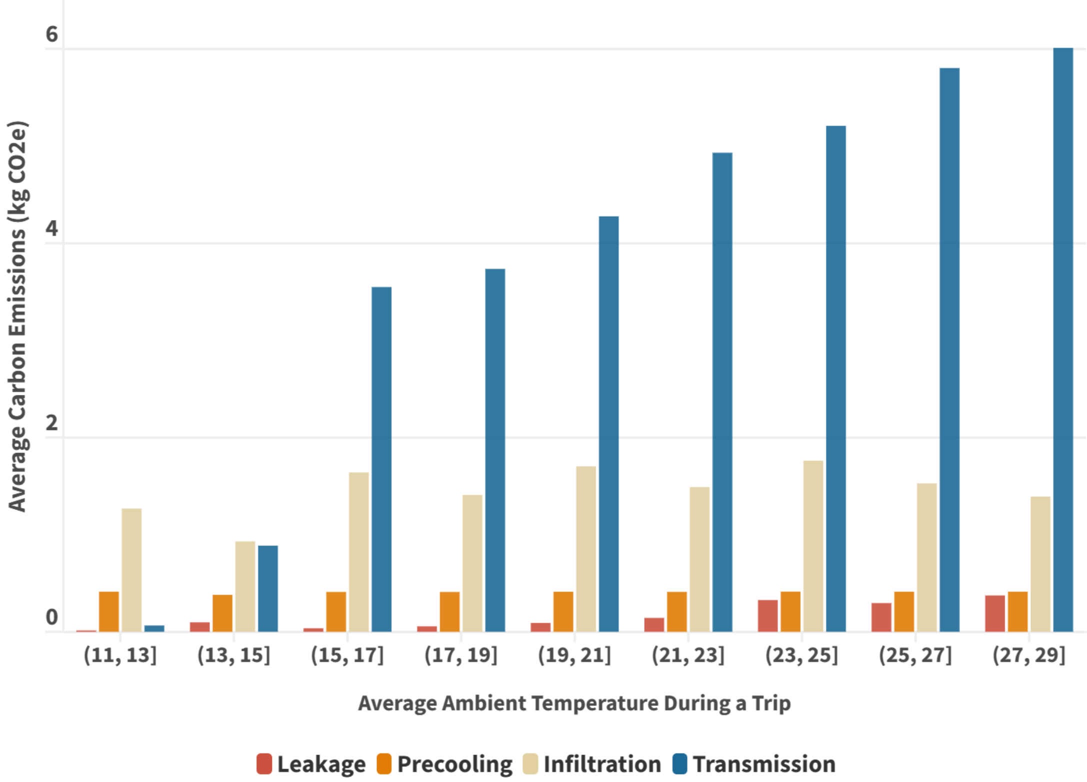

Figure 4 Variability in refrigerant leakage and refrigeration-related carbon emissions across different ambient temperatures

3.3 Model performance evaluation

To evaluate our model's performance, we compared model-derived fuel consumption with actual data captured by sensors. The accuracy of the model is assessed using the percentage gap (%), calculated with Equation (12). This metric quantifies the deviation between the predicted ($\hat{y}_i$) and the actual (y_i) values, as follows:

$$100 \times (\hat{y}_i - y_i)/y_i \tag{12}$$

Figure 5 depicts the distribution of the gap metrics for our model, which range from -30% to +40%. The results demonstrate our model's superior estimation accuracy, with an average gap of only 0.72%, indicating a high level of precision in fuel consumption predictions.

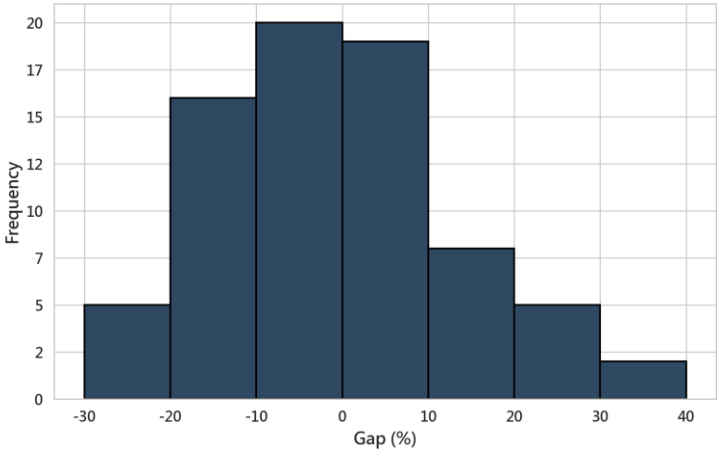

Figure 4 Distribution of model accuracy gap (%)

4. CONCLUSIONS

This study significantly advances green logistics practices and supports the transition towards a net-zero future by meticulously identifying high-emission activities across different operational phases of cold chain logistics. By leveraging real-world data from 73 long-haul trips, our comprehensive bottom-up carbon emission model delineates emissions arising from transport, unloading, and loading phases, as well as from driving, refrigeration activities, and refrigerant leakage. Notably, the robustness of our model is validated by its average error rate of 0.72%, demonstrating precise alignment between the predicted and actual fuel consumption. Furthermore, our findings underscore the substantial impact of ambient temperature on refrigeration emissions, with variations up to 4.5 times, dependent on temperature fluctuations between 11 and 29 degrees Celsius. Such insights are crucial for designing targeted strategies to reduce emissions, particularly in areas significantly influenced by operational conditions such as door operations during unloading and pre-cooling during loading.

As we delve deeper into assessing the impact of varying vehicle sizes and temperature settings within TRUs on emissions, our study reaffirms its commitment to enhancing sustainability. We are actively pursuing innovative methods to decarbonize cold chain logistics, with a particular focus on the electrification of TRUs. These efforts are designed to not only boost the resilience and sustainability of transportation systems but also to align with international initiatives aimed at mitigating climate change impacts. Through this research, we provide critical insights that aid in the adaptation and advancement of green logistics practices, playing a pivotal role in the global shift towards a sustainable, net-zero emissions future.

5. ACKNOWLEDGMENTS

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A Comprehensive Methodology for Sustainable and Climate Resilient Transport Network

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ABSTRACT

Infrastructure networks, crucial for local mobility, face significant exposure to the impacts of climate change. The disruption of key links within these networks due to climate exposures has the potential to isolate entire communities, cutting off access to essential public facilities such as schools, hospitals, and markets. The use of advanced digital solutions offers a new approach to anticipate, mitigate and adapt to future constraints on the network. ORIS Materials Intelligence, the first construction materials platform dedicated to a smart use of construction resources and low impact infrastructure, proposes an innovative Climate Resilience Methodology based on Artificial Intelligence and advanced algorithms to ensure the development of robust transport infrastructure, capable of withstanding climate change while aligning with global decarbonization goals. This methodology is based on multicriteria analysis and is split into: climate screening; study of the infrastructure vulnerabilities; combined analysis, where the infrastructure conditions are coupled with the climate exposures assessed; Social and economic impact identification; calculation of a United Score, which consists of a weighted average of the infrastructure exposure risk, result of the combined analysis, and the social impact identified. A sensitivity analysis helps decide what would be the most appropriate weightings to be used. The United Score drives the adaptation and mitigation measures to be proposed. Adaptation proposals are designed to enhance infrastructure resilience to the assessed climate exposures. Mitigation proposals are based on the Life Cycle Assessment approach, identifying the reduction potential of the Greenhouse Gases (GHG) emissions at various stages of the infrastructure service life. All adaptation and mitigation measures are quantified, priced and compared with the project's overall materials quantities and costs. The Climate Resilience Methodology of ORIS provides an essential tool for policymakers and infrastructure planners, offering a clear, accessible, and practical perspective on what measures should be planned for climate change.

Keywords: Climate Resilience, Climate Risk Assessment, Infrastructure Network

1. INTRODUCTION

The motivation for creating a novel methodology to consider climate projections, infrastructure vulnerability studies, and social and economic aspects into one single tool, arose from the gap identified in the literature about climate change assessments and conceptual frameworks for evaluating infrastructure risks. Up until now, there seems to be no digital tool to allow policymakers to fully understand how infrastructures can be impacted by extreme climate events, what would be the population impacted in case of disruptions, and what would this mean in terms of adaptation measures and financial investment. This new methodology is not only conceived to fill this gap, but also to couple adaptation and mitigation assessments in one single digital tool. With adaptation and mitigation strategies being assessed in parallel, GHG emissions can also be evaluated considering various design scenarios of adaptation.

The paper begins with a background and literature review in order to understand the need for a digital tool and then presents the novel methodology proposed. Further in the paper, each step of the methodology is described and explained in detail. The chapter of discussions is dedicated to present and discuss the limitations and potential improvements of the methodology. The paper concludes by highlighting how the ORIS Climate Resilience Methodology empowers policymakers with a comprehensive tool for assessing and enhancing infrastructure resilience.

2. BACKGROUND AND LITERATURE REVIEW

Climate exposure evolutions can be evaluated using climate projections, which are rigorously generated through coordinated efforts by organizations like the World Climate Research Programme (WCRP) and the Intergovernmental Panel on Climate Change (IPCC). Generating these projections involves sophisticated climate models that integrate atmospheric, oceanic, and terrestrial data to simulate the Earth's system dynamics. These climate models are developed by different research institutes around the world and their outputs depend on various input parameters that can vary from model to model. An important input parameter, for example, is the Shared Socio-economic Pathway (SSP), which represents the socio-economic scenario to be expected in the future in terms of climate policies to be implemented, greenhouse gasses emissions, and land use, for instance. The various SSP scenarios are defined in the IPCC Assessment Reports, the latest being the 6th Assessment Report. Once the inputs are well defined, those climate models generate projections for any past or future periods. Projections anomalies for future periods are often applied to historical observation data to predict future climate.

Despite substantial research efforts and advancements on conceptual frameworks to evaluate climate exposures and suitable adaptation and mitigation strategies to be proposed (ITF, 2016; OECD, 2018), a critical gap remains in the development of a digital tool that seamlessly integrates climate resilience assessment with transportation infrastructure decision-making. The existing literature underscores the need of such a tool in order to operationalize the concept of resilience (Yang, Z. et al, 2024) and, therefore, to help guide policymakers towards informed decisions that enhance infrastructure resilience.

3. ORIS CLIMATE RESILIENCE METHODOLOGY

The ORIS Climate Resilience Methodology is designed to evaluate and enhance the resilience of transport infrastructure through a multi-step approach that combines climate screening, infrastructure vulnerability assessment, and the identification of social and economic impacts. The methodology is resumed in Figure 1.

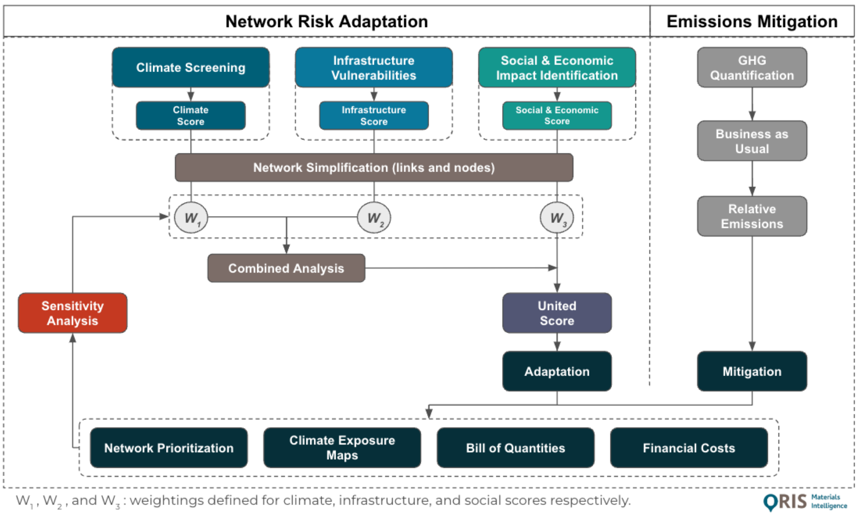

Figure 1 ORIS Climate Resilience Methodology.

(ORIS Materials Intelligence, 2024)

The foundation of the methodology is composed of three axes: the Climate Screening, the Infrastructure Vulnerabilities, and the Social and Economic Impact Identification. Each one of these axes yield a different score: climate score, infrastructure score, and social and economic score, which are then used to classify sections of a whole infrastructure network. Those scores vary in the integer values range of 1 to 5, comprising a risk classification varying among lowest (1), low (2), medium (3), high (4), or extreme (5). In this methodology, the network is a mathematical graph simplification, where roads, streets and rails are considered links and every link edge, or points of interest are considered nodes. The network is created with geometries extracted from OpenStreetMap and Here Maps. The climate score is evaluated together with the infrastructure score in order to classify the impacts of each climate exposure on each infrastructure link. This classification is done in the Combined Analysis step and it outputs an infrastructure exposure risk classification, which allows for understanding what will be the most vulnerable links of a network in case of an extreme weather or climate event. After that, social and economic impacts are identified in order to measure the impact that the critical links could have on the benefiting population and on the local freight transport. This coupling between the Combined Analysis and the Social and Economic Impact Identification leads to a United Score, which also varies in the same integer range from 1 to 5 and allows for prioritizing links out of a whole network and deciding where adaptation and mitigation plans should be foreseen. All steps of this methodology will be described in detail in the next few chapters.

3.1Climate screening

The first step in the methodology involves defining the most relevant climate exposures for the infrastructure region. As default, these exposures include heat, freeze-thaw cycles, flash flooding, and infrastructure immersion, but, depending on local data available, can also include other indicators, such as land sliding and silting. The methodology also requires the definition of key parameters for climate projections, such as the Shared Socioeconomic Pathways (SSP) to be considered, the future period for projections, which can be a specific year or an interval between two specific dates, and the choice of the most suitable climate model. Climate models vary in their input parameters and simulation methods. For every different project, a sensitivity analysis is carried out with the goal of choosing the most suitable climate model based on the comparison of their projections with historical observations. The model providing projections with the lowest variation compared to observations is chosen as the most suitable one.

Both global and regional climate models, GCMs and RCMs respectively, are evaluated for their performance against historical data. The methodology incorporates the latest phase of the Coupled Model Intercomparison Project (CMIP), specifically CMIP6, to ensure accurate climate exposure evolution maps. With the projections generated from climate models, the climate exposures can be evaluated. The next few chapters are dedicated to give more detail on how each variable is calculated and taken into account in the context of the methodology being presented.

In the climate axis of this methodology, three data sources are used in order to carry out sufficiently precise analyses:

- Historical data: data source from the Climatologies at high resolution for the earth's land surface areas (CHELSA);
- High resolution rainfall data: the major source used is the ECMWF Reanalysis v5 (ERA5) data. The consideration of ERA5 data is paramount when evaluating flood risks due to its detailed and high-resolution historical weather records;
- Projection data: the sources considered come from the more than 100 climate models that are part of the Coupled Model Intercomparison Project Phase 6 (CMIP6).

Those data are automatically treated before generating climate exposures that help identify if an infrastructure could be exposed to climate events. The data processing included in the methodology is the subject of the next section.

Data processing: statistical downscaling and clustering

When assessing the evolution of a particular climate exposure (e.g. heat, freeze-thaw cycles, and flooding), historical observations are computed together with climate projections obtained from CMIP6 climate models. This computation is done using a technique of statistical downscaling. Figure 2 shows a schematic representation of this process from its input data until its output risk classification.

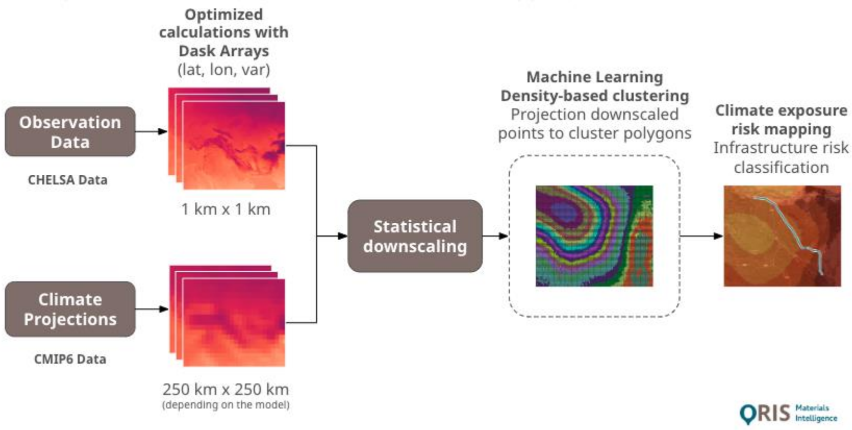

Figure 2 Statistical downscaling and clustering of climate data.

(ORIS Materials Intelligence, 2024)

Further in the climate exposure subsections, climate exposure maps are shown to demonstrate how the results of this data processing are displayed on the ORIS digital platform using the climate exposures heat, freeze-thaw cycles, and flooding as examples. The figures to be shown as examples are based on a successful project developed in Uzbekistan, where a whole network assessment was conducted in order to prioritize roads to be adapted. It is important to note that the methodology is in constant development with the goal of increasing the number of climate exposures to be assessed from the climate screening until the proposition of tailor-made adaptation measures.

Climate Exposures: Heat

The heat exposure is by computing the maximum 2-m air temperatures historical data from CHELSA together with maximum 2-m air temperature projections from the most suitable CMIP6 climate model. The data is passed through a statistical downscale and clustering before being available on the ORIS digital platform. Figure 3 displays an example result of how the exposure map is shown for a project in Jizzakh, Uzbekistan.

Figure 3 Heat climate exposure displayed on the ORIS digital platform.
(ORIS Materials Intelligence, 2024)

Freeze-thaw cycles

The freeze-thaw cycles indicator is calculated using the same historical datasets and climate projections used for heat exposure. The higher spatial resolution from observation data is used to improve the projection resolution through statistical downscaling. Analogously, the higher temporal resolution from historical data is used to fill gaps in time from climate projections through time-series regression. This regression is used for developing the freeze-thaw cycles indicator and the procedure follows the same calculation methods presented in CHELSA (Karger D.N. et al, 2017). The results are automatically integrated with the ORIS digital platform and an example can be checked in Figure 4.

Figure 4 Freeze-thaw cycles climate exposure (frost) displayed on the ORIS digital platform.
(ORIS Materials Intelligence, 2024)

Flooding

The flooding assessment is split into two different but complementary evaluations:

- Assessment of runoff risk: associated with flash floods;
- Assessment of infrastructure immersion risk: associated with long-term floods.

Assessing runoff risk is a complex task. One significant challenge in modeling flash floods is the accurate representation of hydrological and hydraulic processes at fine spatial and temporal scales. Flash floods involve quick runoff generation and rapid changes in water levels, requiring detailed modeling of both surface and subsurface flows. The complexity is further increased by the need to incorporate diverse environmental factors, such as soil moisture, land cover, topography, and urban infrastructure, which all influence flood dynamics. Great research work has been developed in order to improve predictability of flash floods, e.g. in (Sayama T. et al, 2020). The current state of the ORIS methodology adopts an adaptation-driven approach to evaluate the risk of flash floods: use of the hydrological rational method (Equation 1) in order to calculate the peak runoff flow along the infrastructure. Furthermore, the use of this method requires the collection of important data on:

Table 1 Data needed for carrying out a runoff risk assessment.

Rational method parameter	Data description	Data source implemented
Maximum rainfall [i, in mm/h]	The maximum rainfall is computed by fitting a Gumbel distribution into the historical daily rainfall data from ERA5.	ERA5 and CMIP6
Catchment area [A, in m2]	The catchment area is computed using the topographic wetness index (TWI) as an algorithm to identify watersheds. Object segmentation algorithms from satellite imagery are also used to validate results.	SRTM data
Runoff coefficient [C – dimensionless]	The runoff coefficient estimate necessitates data on soil type and vegetation index in the region of interest. Data for this can come from object segmentation using satellite imagery or land cover estimations already done by the Copernicus institute.	SRTM data and Copernicus Climate Data Store

With all these parameters, the runoff flow (Q, in m^3/s) can be calculated using the rational method, Equation 1.

$$Q = C \cdot i \cdot A \quad (1)$$

The results of this runoff calculation are used to design or resize the hydraulic structures of the infrastructure links prioritized as adaptation proposed in the end of the ORIS climate resilience methodology. The infrastructure immersion risk is evaluated using a very comprehensive dataset provided by a powerful tool called Aqueduct, (Philip J. et al, 2020). This data source contains vast amounts of data on the observed coastal and riverine floods, as well as estimation of flood-prone areas evolution considering projections from selected climate models. The data helps understand if an infrastructure is located in a flood area and what is the estimated water depth of flood expected on each pixel of the data grid. The results are automatically integrated with the ORIS digital platform and an example considering both runoff and immersion risks can be checked in Figure 5.

Figure 5 Flooding climate exposure displayed on the ORIS digital platform.
(ORIS Materials Intelligence, 2024)

3.2Infrastructure vulnerabilities

Evaluating infrastructure vulnerabilities is essential to understand how climate exposures could impact infrastructure links. The infrastructure score is determined by considering indicators that highlight vulnerabilities: infrastructure surface layer condition, General User Delay (GUD), and traffic.

Surface layer condition

Evaluating the condition of infrastructure layers is a critical component of ensuring the resilience and sustainability of transport networks. This evaluation typically involves assessing various factors such as surface distress, structural integrity, and functional performance. The study carried out by (Bennett C.R. et al, 2006) is still of interest nowadays, as it highlights the issues related to data availability and the implications for road management practices. These methods provide valuable insights, but one of the most significant challenges in this evaluation process is the availability and accessibility of reliable data. Accurate and up-to-date data on surface layer conditions are essential. Unfortunately, such data are often scarce or inconsistent, particularly in regions with limited resources or less developed data collection infrastructure. In the case of the ORIS climate resilience methodology, the surface layer state of a whole network is considered using interpolation and merge methods of different regional and reliable data sources. Those data sources are a mix of open source, closed source data, and data enrichment through machine learning techniques, such as density-based clustering algorithms.

Traffic

The traffic score that is calculated in this step comes from a standard traffic assignment usually carried out in transportation planning projects. Because of the lack of precise data on the Origin-Destination matrices for every administrative region of the world, the methodology used is a simplification of the Four-Step Model (Manheim, 1979; Florian et al., 1988). As not all steps of this model (trip generation, trip distribution, mode choice, and traffic assignment) can be followed in a global coverage, here is the major approach of the trip distribution step: the trip distribution phase aims at distributing the trips generated by the previous step. For this project, a gravitational model (Suzanne P. Evans, 1973) has been used to estimate the attractiveness of each centroid (city/town) when it comes to traffic demand. The gravitational formula used as an estimator for this project is described in Equation 2 (Sheffi, Yossi, 1984). Equations 3 and 4 are necessary to deal with the limitation of not having Origin-Destination (O-D) surveys available in order to estimate traffic production and demand.

$$T_{ij} = K\frac{O_i \cdot D_j}{d^2} \tag{2}$$

Where: T_{ij} is the number of trips from the origin zone i to the destination zone j; K is a factor to be calibrated; O_i is the population from the origin zone i; D_j is the population from the destination zone j; d is the distance between the origin i and the destination zone j.

As the origin-destination survey is often missing, the variables K, O_i, and D_j are estimated, as follows in the set of Equations 3, 4, and 5, in order to obtain a rough estimation of the number of vehicles that are used in the trip movement in the most recent year of data availability. The data sources used for this estimation is a mix of the World Bank Data catalog and regional statistical data from local authorities of different countries, such as the Statistics Agency of Uzbekistan (https://stat.uz/ru/) and the Australian Bureau of Statistics (https://www.abs.gov.au/).

$$K = \sum_{pf=1}^{t} \sum_{\square}^{n} w_{pf} \tag{3}$$

$$O_i = v_i \cdot t_i \cdot P_i \tag{4}$$

$$D_j = v_j \cdot t_j \cdot P_j \tag{5}$$

Where: v is the vehicle factor, expressed by the number of vehicle registration per inhabitant in the region of interest; t is the trip percentage and it should be calibrated using regional data. Local statistical bureaux are often a very good data source; P_i is the population from the origin i. This allows for generating coherent trips from i to j.

As an hypothesis taken for this methodology, the K factor, defined in Equation 3, is considered as a public facilities attractiveness score, which helps fill the gap created by the lack of precise O-D surveys using public facilities as attractivity factors for distributing trips. The factor K depends on the following parameters: pf, which is the public facility type and t is the total number of public facilities types in the destination zone; $\sum_{\square}^{n} \square$, which is the count of the total number (n) of public facilities of type pf in the destination zone; w_{pf}, which is the weight used for each public facility. Double weight has been used for hospitals and schools.

The traffic assignment was carried out using an all-or-nothing assignment (Sheffi, Yossi, 1984). It assumes that there are no congestion effects and that all drivers perceive route choice the same way. The result of the traffic assignment is the traffic passing on each link of the network.

General user delay

The process of General User Delay (GUD) evaluation is based on a detailed modeling and simulation of the transport network to predict traffic flow patterns under normal and disrupted conditions. The results of the traffic estimation are used to estimate the increase in travel time on every network link when they are disrupted. As of the publication date of this paper, the zones considered for this evaluation are the cities and towns of a region of interest pre-set before the resilience assessment. This indicator is calculated by computing the distance skim matrix (DSM). In this evaluation, the average nominal speeds are considered constant and traffic jams and lights are not taken into account, i.e. a free flow is assumed for the whole network.

The sequence used for calculating the GUD criticality map is as follows considering a network with n links: compute the original DSM for the full network for all zones of interests; for each link l: create a new network graph while excluding l - Θ_{i-l} - then compute the resulting DSM, Θ_i; compute the difference between the average sum on all dimensions of the two DSM matrices; convert it into a time unit based on hypotheses on the uniformity of speed v and trip distribution. The final time GUD score of each link could be then formulated by Equation 6.

$$GUD(l) = \frac{1}{v}\sum_{i=0}^{n}\frac{\Theta_{i-l} - \Theta_i}{m} \quad (6)$$

The results of this evaluation are appealing for infrastructure planners. By classifying network links according to their disruption risk, it becomes possible to prioritize investments and interventions aimed at enhancing network resilience. For instance, links with high disruption risks can be targeted for structural reinforcements, improved drainage systems, or better alternative route planning.

3.3 Combined analysis

The Combined Analysis step involves coupling the assessed infrastructure vulnerabilities with climate exposures. This analysis is critical as it identifies which infrastructure links could be impacted or disrupted by climate events based on the vulnerabilities studied. The output of this analysis is called infrastructure exposure risk and is used together with the social and economic score in order to compose a comprehensive final scoring for the network links.

3.4 Social and economic impact identification

Rural connectivity

The Rural Connectivity indicator is calculated based on the existing Rural Access Index (RAI) (World Bank Group, 2016) and on possibilities of scaling this indicator to allow link prioritization. Rural Connectivity is expressed by the rural population density living around a link. This new indicator allows for having a more granular view on how the link is important in terms of rural population connected living under 20-25 min walking distance. The steps taken to generate the score for this indicator are: selection of commonly used tags from OpenStreetMap (Trunk, Primary, Secondary, Tertiary) that serve as an approximation for all-season roads; creation of a mask based on 2.5 km buffer on these roads; mapping only the rural areas by subtracting the urban areas as defined by the Global Rural-Urban Mapping Project (Center for International Earth Science Information Network, 2021); calculating the amount of rural population that are up until 2.5 km far away from a road in, at least, good condition.

Accessibility to public facilities

The accessibility to public facilities is evaluated through a disruption simulation analysis. In this analysis, every link of the infrastructure network is disrupted one by one in order to understand if some links are crucial for connecting population to hospitals, schools, and markets, for example. If a link disruption leads to an isolated population that could not access public facilities without that link, this link is associated with an extreme accessibility risk. This indicator is very important to understand which links could impact the population the most when an extreme weather or climate event happens. The result of this analysis also helps prioritization of maintenance investments to keep a well-connected population. This indicator is calculated by carrying out an iterative graph analysis of the infrastructure network. In each iteration a link is deleted from the network and its impact on the creation of isolated islands are evaluated using programming algorithms in Python.

3.5 United score and network prioritization

The united score is one of the most important outputs of the ORIS climate resilience methodology. It is the computation of the final risk score of each link after evaluating climate, infrastructure vulnerabilities, and social and economic impacts. It is the weighted average of each one of the climate, infrastructure, and social and economic scores. As the results of each score are intrinsically related to each other - a link can cause social and economic impact if it is disrupted due its vulnerabilities to the climate exposures assessed - the weights to be considered are issued from a sensitivity analysis. This analysis is necessary to correctly account for all scores of the methodology. This analysis avoids considering wrong hypotheses that could culminate in neglecting some scores that are classified as high (4) or extreme (5).

The weights indicated by W_i, where i indicates each score calculated, can vary between 0 and 1. The composition of the united score is shown in Equation 7.

$$United\ score(l) = W_0\ Climate(l)\ + W_1 Infrastructure(l) + W_2 Social(l) \tag{7}$$

In Equation 7, the parameter l is used to indicate that the calculation of such an equation is carried out for every link of the infrastructure network. This allows for a comparison between every link of a whole network and ultimately the prioritization of the most critical infrastructures. From this prioritization, efforts and investments can also be prioritized according to adaptation and mitigation strategies proposed for the most critical links.

3.6Adaptation and mitigation strategies

After the prioritization phase, when the result of the united score is used to identify the most critical infrastructure, adaptation and mitigation strategies are automatically proposed and displayed on the ORIS digital platform. The adaptation proposals are designed to enhance infrastructure resilience to the assessed climate exposures. Examples of such adaptations are employing rigid pavement as the surface layer, using stabilized bases and foundations, dimensioning or resizing culverts and ditches for extreme rainfall events, and reinforcing foundations or embankments to prevent water immersion.

The mitigation proposals are based on the Life Cycle Assessment approach, taking into account: the quantification of the Greenhouse Gases (GHG) emissions at various stages of the infrastructure service life, the quantification of possible emissions of a Business-as-Usual scenario, and the calculation of the relative emission between these two first quantifications. Possible measures to be proposed include strategies like the use of low-carbon materials to reduce carbon emissions, optimized long-term maintenance programs, as well as compensation measures, e.g. reforestation, which supports absorbing carbon dioxide from the atmosphere.

4. DISCUSSION

The ORIS climate resilience methodology offers a comprehensive digital tool that aims at facilitating decision-making through informed decisions on climate change, infrastructure vulnerabilities and social and economic important aspects. The methodology is in constant development and is improved considering the state-of-the art research on climate science, artificial intelligence, and infrastructure risk evaluation.

Some points that deserve special attention are the following: the choice of the parameters that compose each one of the three scores presented is based on previous research and experience from previous projects, which means that it is constant development and improvement; methods to calculate surface pavement temperature from 2-m air temperature vary in their hypotheses taken and their results; the traffic parameter from the infrastructure score is created based on simplifications made from the four-step model (FSM). Usually this method requires at least a phase of Origin-Destination survey in order to correctly estimate demands and attractions of traffic from each pair O-D. Nevertheless, these surveys are usually time-consuming and not carried out in all countries. The major hypothesis taken in order to estimate traffic in no matter the region of the world generated good results, but, as it is an estimation, those results are only good when it comes to comparison of links. The results should not be taken by their absolute values, but only comparatively and the comparison between two outputs for different geographical regions could lead to erroneous conclusions; moreover, further research should be done in order to better understand the best materials adaptation measures to be implemented in every different climate event assessed; a multi-risk assessment is also the subject of further improvements of this methodology.

Even though a lot of room for improvement is identified for this methodology, the most important objective has been achieved, which is the development of a digital tool that supports network infrastructure decision-making. The tool is in continuous improvement and new versions that address those limitations will be published in the future.

5. CONCLUSION

The ORIS Climate Resilience Methodology represents a significant advancement in the field of infrastructure resilience and climate risk assessment. By integrating climate projections, infrastructure vulnerability assessments, and social-economic impact analyzes into a digital platform, it provides a robust framework for policymakers and infrastructure planners to make informed decisions to make transport infrastructures more climate-resilient. Key contributions of this methodology include the development of a multi-criteria analysis approach that considers climate screening, infrastructure vulnerabilities, and social-economic impacts. The resulting United Score offers a comprehensive measure of risk that guides the prioritization of adaptation and mitigation measures. These measures are quantified and priced, ensuring that they are practical and economically viable. The wide range of data sources used to generate the United Score, from high-resolution historical climate data to climate model projections and other open-source data, ensures that the assessment is replicable for different projects around the world.

Despite the innovative aspect of the methodology, a considerable room for improvement has been identified. Enhancements in the estimation of traffic patterns, the integration of surface pavement temperature models, and the development of a multi-risk, and even a multi-hazard, assessment are identified as critical points and are already the subject of ongoing research and development.

The methodology presented in this paper offers an innovative tool that bridges a gap between climate science and infrastructure planning. It empowers decision-makers with the information needed to plan for more resilient infrastructure that can withstand the impacts of the changing climate. As the methodology evolves, it is hoped that it plays a crucial role in shaping the future of sustainable and resilient transport networks.

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Capacity Needs Assessment and Review of Existing Methods and Tools for Assessing Loss and Damage from Climate Change for Road Infrastructures in Cambodia

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ABSTRACT

Cambodia is one of the most disaster-prone countries in Southeast Asia due to frequent seasonal floods and other climatic events, and this has become a major threat to road sector. A project on "appropriate costing methods of climate change adaptation in infrastructure development: experimental studies for road infrastructure projects in Cambodia" has been implemented, with a goal to enhance the climate resilience capacity of roads development sectors in Cambodia. The project also covers capacity needs assessment and a review of methods and tools for the assessment of loss and damage from climate change impacts on roads infrastructure. Mixed method is used, and secondary data collected from journal articles, reports and primary data from questionnaire survey with concerned ministries. The study provides a critical state-of-the-art review of frameworks, approaches, methods, and tools from building road resilience to climate change. It was found that concerned government staff have average capacity to strategy, system, and support knowledge and tools to conduct assessment of losses, damages and adaptation costing methods, while the capacity and knowledge on "skills and technical methods" remain limited. For assessing loss and damage, existing frameworks emphasized relationship between loss/damage from climate stressors and vulnerability, risk management, impacts, coping mechanisms, and adaptation. Damage functions normally include two distinct approaches emerge such as 'absolute damage' functions, quantifying direct monetary losses based on flood depth, and 'relative damage' functions.

Keywords: Capacity Assessment, Climate Change, Loss, Damage, Road Infrastructure

1. INTRODUCTION

The mean annual temperature of Cambodia is expected to rise by 0.7– 2.7°C by the 2060s and 1.4 – 4.3°C by the 2090s (McSweeney & Lizcano 2008). Cambodia is one of the more disaster-prone countries in Southeast Asia, affected by floods and droughts on a seasonal basis. Cambodia's vulnerability to climate change is linked to its characteristics as a post-civil war, least developed, predominantly agrarian country, with nearly 80% of the population living in rural areas. Weak adaptive capacity, poor infrastructure, and limited institutions exacerbate the country's vulnerability to climate variability and change. Indeed, floods and droughts are recognized by the government as one of the main drivers of poverty. During the 20 years from 1987 to 2007, a succession of droughts and floods resulted in significant loss of life and considerable economic loss. Most of the damage to national and provincial roads, and irrigation systems occurs during the annual flood season (August-November) with marked peaks in

September and October corresponding to the period of the greatest depth of flooding over large tracts of the country.

Road infrastructures are one of the most important assets in the world due to the dependency on other critical infrastructures upon it. Cambodia is one of the most disaster-prone countries in Southeast Asia due to frequent seasonal floods and other climatic events, and this has become a major threat to road sector. The Master of Science in Climate Change Program (MCC) of Royal University of Phnom Penh formed a consortium with the Asian Institute of Technology in Thailand and University of Freiburg in Germany have implemented the project on "appropriate costing methods of climate change adaptation in infrastructure development: experimental studies for road infrastructure projects in Cambodia". The project goal is to enhance the climate resilience capacity of roads development sectors in Cambodia. However, this project focuses on the review of frameworks and approaches for the assessment of direct loss and damage from climate change impacts on roads infrastructure. This study is aimed to assess capacity of concerned government staff of Cambodia and review of tools and methods used to assess damages and losses from climate change for road and related infrastructure. The scope of the report involves a comprehensive examination of the vulnerability of Cambodia to climate change, with a particular emphasis on the recurring issue of flooding.

2. LITERATURE REVIEW

2.1 Classification of Loss and Damage

The United Nations Framework Convention on Climate Change (UNFCCC) has defined loss and damage in the context of climate-related risks as encompassing not just what can be reduced through adaptation measures but also additional impacts that cannot be mitigated (UNFCCC, 2014). Additionally, the definitions of losses and damages vary, and examine in the context of the current knowledge regarding the impacts of extreme weather events. Mechler et al. (2019) defined "losses" primarily refer to monetary losses, whereas "damages" encompass non-monetary consequences and irreversible effects. Losses stemming from extreme weather events can include both types, such as monetary losses associated with property damage that can be repaired or replaced, as well as non-monetary impacts like loss of life, health effects, and irreparable damages such as coastal erosion, ecological consequences, and societal impacts like forced relocation following severe flooding. Losses in the context of climate-related risks are associated with irreversibility (e.g., fatalities, poverty traps), while damages are rectifiable impacts. A useful distinction has been made between avoided, unavoided, and unavoidable loss and damage (Verheyen and Roderick, 2008). Loss refers to irreversible impacts such as loss of income and food security from crop failure or land loss from rising sea levels. Damage refers to impacts requiring monetary repair such as flood or cyclone damage to boats, homes, and roads (Action Aid, 2019). The understanding and quantifying loss and damage from climate related hazard is an important step towards up-taking responsibility to measures the risk reduction. It plays a crucial role in informing decisions and setting priorities for climate change mitigation and adaption for towards sustainability.

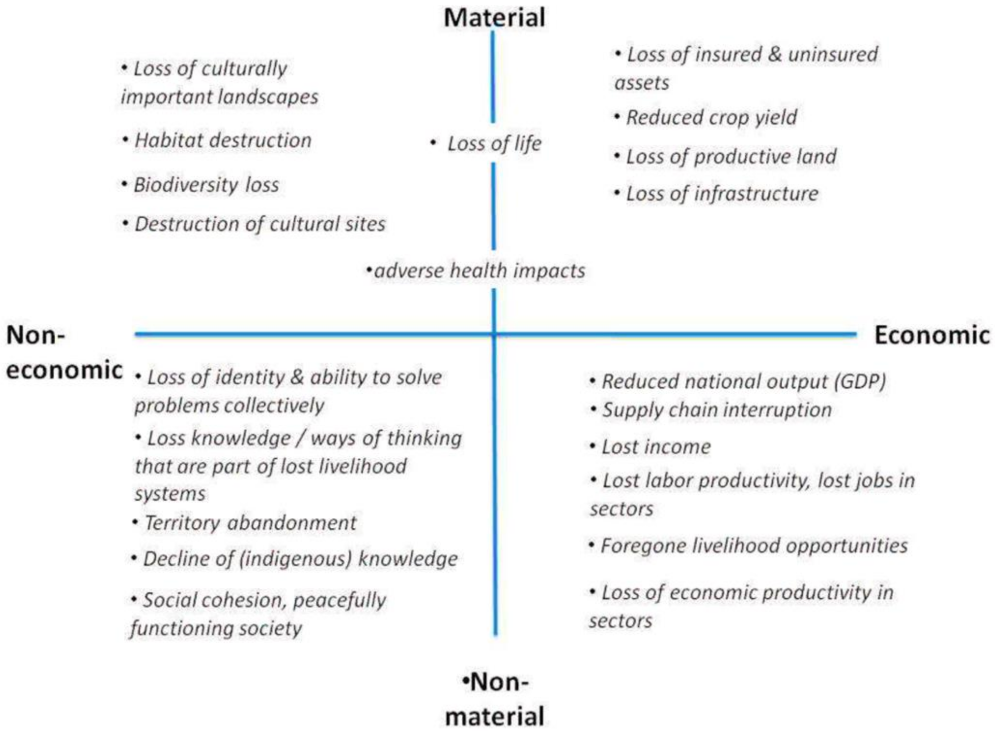


Figure 1: Example of Economic and Non-Economic Losses with Material and Non-Material
Source: Morrissey, J., & Oliver-Smith, A. (2013)

2.2 Direct and Indirect Economic Loss and Damage

Direct economic loss is the economic damage generated directly by natural disaster, for example, the damage of buildings, roads, production facilities, the indoor property loss, etc. Basically, these losses can be measured by the repair or replacement costs of the damaged structure and properties, including building contents and business inventory (Brookshire et al. 1997; Lindell and prater, 2003; FEMA, 2001). These direct losses are readily observable and evident as they stem directly from the impact of the natural disaster. According to Brookshire et al. (1997), indirect losses extend beyond direct physical impacts and encompass factors like income losses and business inventory losses. In addition, the indirect loss as the result of a multiplier or ripple effect throughout the economy due to supply bottlenecks and reduced demand triggered by direct losses. As, Burrus et al. (2002) specifically associate indirect loss with decreases in economic output resulting from business disruption or interruption. Notably, different studies, including those by Enke et al. (2007), Rowshandel (2000), and FEMA (2001), introduce variations in the detailed definitions and boundaries of indirect economic loss. CGER (1999) provides a comparatively structured definition and boundary for indirect economic loss. CGER categories indirect economic loss into three groups: induced loss, linkage loss, and spending reduction. The indirect impacts of flooding are a result of a loss in the flow of goods and services to the economy (Messner et al., 2007). These costs are in terms of traffic delays, production losses, or emergency expenditures.

2.3 Avoided, Unavoided, and Unavoidable Loss and Damage

Verheyen (2012) differentiates between avoided, unavoided, and unavoidable Loss and Damage. Effective action must be taken to prevent loss through mitigation and adaptation, while recognizing that some loss may be unavoidable. A range of approaches, such as insurance and social safety nets, can aid in addressing residual loss. The success of these efforts will depend on adequate resources for adaptation and coping. The UNU framework (Adger, 1999; McLeman, 2010; Moser and Ekstrom, 2010) highlights the relationship between loss/damage from climate stressors and vulnerability, risk management, impacts, coping mechanisms, adaptation, and limits/constraints of adaptation. The framework emphasizes that a household's vulnerability profile, risk reduction measures, and response to impacts, including coping strategies and adaptation, ultimately determine the presence of residual loss and damage. This approach offers a comprehensive understanding of the interplay between various factors that contribute to loss and damage in the face of climate change.

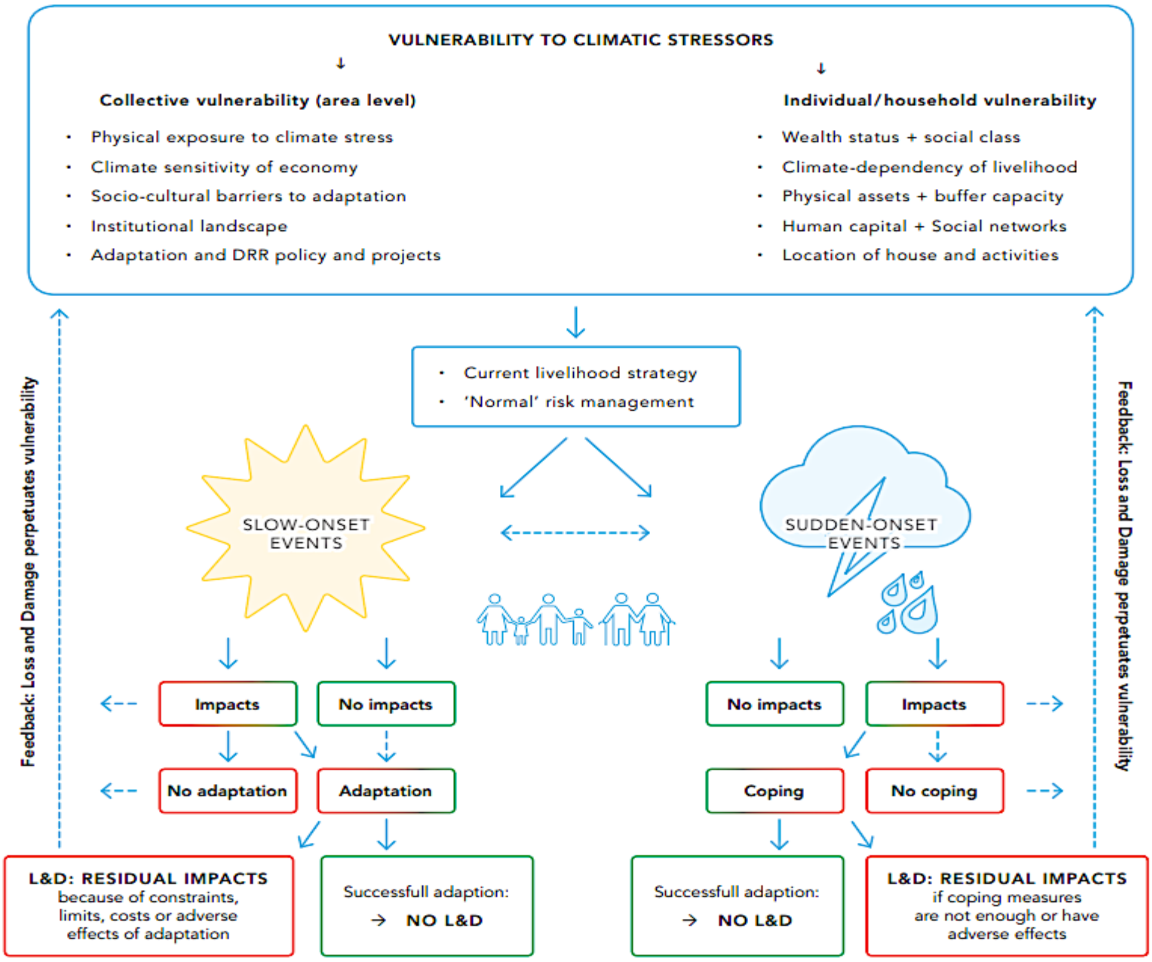


Figure 2: Conceptual Framework: Linking Loss and Damage to Vulnerability Risk Management and Adaptation
Source: Warner and van der Geest, 2013

Reactive adaptation (responding to actual impacts) and pro-active adaptation (responding to expected impacts) are key components in reducing loss and damage from climate change. The household's adaptive capacity and the magnitude of the climatic stressor determine the effectiveness of coping and adaptation measures in avoiding residual loss and damage. Insufficient or costly measures result in loss and damage, which in turn increases household vulnerability to ongoing climatic changes and future extreme events (Warner and van der Geest, 2013).

3. METHODOLOGY

3.1 Approach and Overall Methodology

This article draws on a mixed-method approach comprising questionnaire study with concerned government staff to the assessment of capacity needs, and secondary data review. For ensuring a comprehensive review the assessment methods and tools for loss and damage, a stepwise procedure was followed for the entails study including 1) **Literature review:** This step involves conducting a preliminary examination of existing tools and methods available for cost estimation under climatic threats and climate change to identify appropriate methods of cost estimation in the Cambodian context, 2) **Results interpretation and justifications:** This step involves analysing the data collected through the literature review and interpreting the results to draw insights and recommendations, and 3) **Conclusion:** This step will involve summarising key findings of the research processes and highlighting the key insights and potential recommendations.

The Capacity Need Assessment (CNA) is developed using the 7S questions for this purpose (the McKinsey 7S model developed in 1978) and materials on capacity need assessment developed by UNDP (UNDP Capacity Assessment Methodology User's Guide, 2008). This questionnaire is divided into two sections. The first section contains two parts: i) technical part including loss and damage analysis, and adaptation costing methods; and ii) Management part consisting of Strategy, Structure, and Style, etc. The Second section is to assess the preference of capacity building strategies and activities, what types of training modalities the staff of each ministry want to have.

3.2 Data Collection Methods

Questionnaire survey was conducted with government officials from Ministry of Rural Development (MRD) and Ministry of Public Works and Transport (MPWT) on the capacity needs and these questions are intended to form the basis for discussion during round table meetings and consultation. The survey was interviewed with 24 technical staff and experts from General Department of Rural Road, General Department of Public Works and Transport, and General Department of Techniques. Qualitative data included the existing information from systematic literature review in determining methods and tools to assess losses and damages. The systematic literature review focused on existing loss and damage assessment approaches that are used in context of road infrastructure - and both peer-reviewed journal articles as well as documentation, publications papers, reports are included.

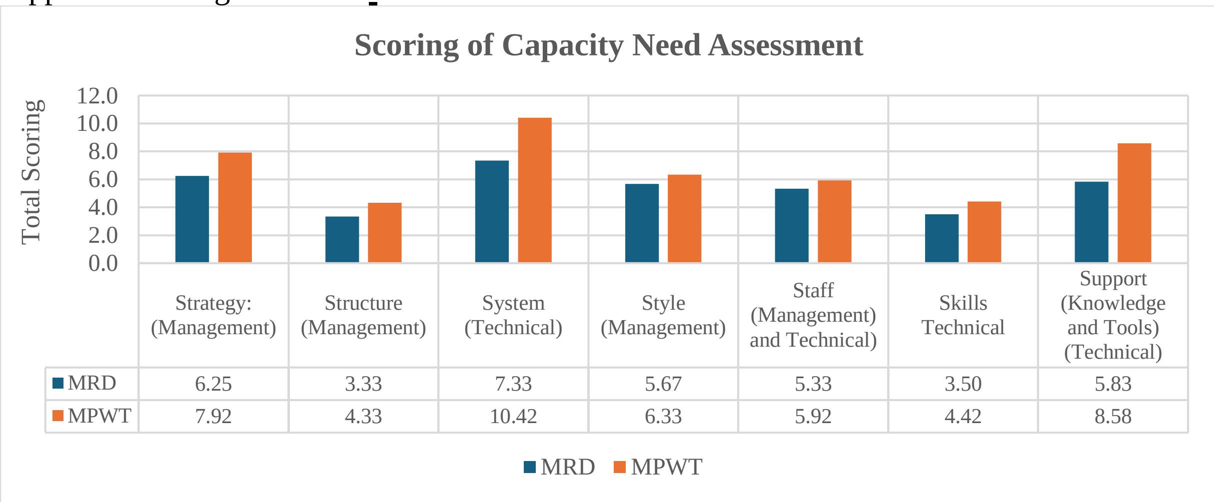
3.3 Data Analysis Methods

This study is based on both qualitative and quantitative methods of analysis. For the assessment of capacity needs was analysed by using descriptive statistic. It filled in and scored by the individual participants at the meeting. Secondary data from different sources were triangulated where appropriate. The review has been carried out through a critical analysis of existing literature by the means of top down and systematic approach. Last but not least, the descriptive analysis is used to develop the comprehensive findings and formulate precise conclusion.

4. RESULTS

4.1 Capacity Needs

The information about the skills and levels of knowledge of the staff from bother MPWT and MRD are important for selecting the proper design and methodology of estimating losses, damages, and adaptation costing on road and its related infrastructures due to climate change. The Capacity Needs Assessment identifies the skills that related government institution has in the use of data analysis, software and the levels of the staff in the use of data analysis and visualization software – to estimate the losses, damages, and adaptation costing due to climate change impacts. Criteria for the Capacity Need Assessment is categorized into seven including 1) strategy of the implementation, 2) structure, 3) system, 4) style, 5) staff, 6, skills, and 7) support knowledge and tools.



	Strategy: (Management)	Structure (Management)	System (Technical)	Style (Management)	Staff (Management) and Technical)	Skills Technical	Support (Knowledge and Tools) (Technical)
MRD	6.25	3.33	7.33	5.67	5.33	3.50	5.83
MPWT	7.92	4.33	10.42	6.33	5.92	4.42	8.58

Figure 3: Result of the evaluation on capacity and need assessment for both MPWT and MRD

Source: Questionnaire Survey with Government Officials (2023)

As seen from the above graphs, a most staff have average capacity to strategy, system, and support knowledge and tools to conduct evaluation and assessment of losses, damages and adaptation costing method. However, both technical staffs from MPWT and MRD are having limited capacity and knowledge on "skills and technical methods" to the adaptation costing model and how it could be used for building adaptation and resilience on road and its related infrastructures development.

During the evaluation and discussion with both MPWT and MRD, the preferences of training and learning techniques had been pointed out. The plenary discussion and decision on training and learning techniques are on the following:

- MPWT provided high priority on development of case studies and field trip for the "use of engaging participatory learning techniques", while MRD evaluated "medium" as a whole.
- MPWT evaluated high for on the job training, hands on training, demonstration projects and field trip to the "innovative informal training/learning methods", while MRD weighed high to only "on the job training". Lastly, MRD has granted high evaluation on Webcast: central trainer demonstrates skill over Internet and participants watch from desktop – may be combined with teleconference, e.g., Webex, and Information

exchange portal: for sharing documents to the "Use of web-based methods for training (especially with technologically able participants)", while MPWT provided low priority – and gave medium scoring to Self-guided computer-based training: e-learning, and Knowledge networks, on-line discussion groups/forums and networking technologies.

Table 1: Preferences of training and learning techniques by MPWT and MRD

No.	Questions	Preferences	
		MPWT	MRD
B1	Use of engaging participatory learning techniques		
	Case studies	H	M
	Small group work	H	M
	Role-plays, debates	L	M
	Field trips	H	M
	Guest speakers	M	M
B2	Innovative informal training/learning methods		
	Staff exchanges	H	M
	Mentoring	M	M
	On-the-job learning	H	H
	Peer learning	M	M
	Hands-on training	H	M
	Demonstration projects	H	M
	Field trips	H	M
	Interactive workshops (that mix training with work tasks)	M	M
B3	Use of web-based methods for training (especially with technologically able participants)		
	Self-guided computer-based training: e-learning	L	M
	Webcast: central trainer demonstrates skill over Internet and participants watch from desktop – may be combined with teleconference, e.g., Webex	L	H
	Information exchange portal: for sharing documents	L	H
	Knowledge networks, on-line discussion groups/forums and networking technologies	M	M

Source: Questionnaire Survey with Government Officials (2023)

4.2 Roads and Damage/Loss in Cambodia

Cambodia's road network spans over 61,000 km, with 16,292 km classified as national and provincial roads managed by the Ministry of Public Work and Transport and 45,242 km as rural roads managed by the Ministry of Rural Development. Conventional methods are primarily used for planning, design, construction, repair, and maintenance, leading to differing levels of cost for each type of road and related infrastructure. This causes a strain on national and provincial budgets for rehabilitation and maintenance. To address this, there is a need for a nationally accepted standard for adaptation costing to be applied by the public and private sectors, which would help save the national budget and optimize the lifespan of roads and related infrastructures in vulnerable provinces. The impacts of climate change on transportation infrastructure are becoming increasingly severe. Floods are causing widespread disruption to roads and related infrastructure, resulting in significant economic losses and connectivity issues. There are two major of flood types in Cambodia: (1) flashfloods, resulting from heavy downpour upstream on the Mekong River, which affect provinces along the Mekong and the southeastern areas of the country; and (2) central area large scale floods, resulting from a combination of runoff from the Mekong River and heavy rains around the Tonle Sap Lake, which affect the provinces around the lake and the southern provinces. The cost of repairing damaged road infrastructure is high, both in terms of expenses and technical demands and places a substantial burden on the national economy and local economic activities. The national budget allocated for the repair and maintenance of roads has risen from 36 million USD in 2010 to 70 million USD in 2017. The budget for rural road maintenance has also increased, from 15 million USD in 2015 to 20 million USD in 2017 (ADB, 2019). Climate change caused 500 km of damage to roads and related infrastructure in 2019, directly affecting 488,611 households and damaging 36,724 ha of crops (NCDM, 2021). The total cost of flood damage in 2011 was 630 million USD. The following table highlights the urgent need for action to mitigate the effects of climate change on transportation infrastructure.

Table 2: Summary of Flood Disaster and Its Effected 1996-2019

Year	*Deaths*	*Injured*	*Houses Destroyed*	*Houses Damaged*	*Directly affected*	*Damages in crops Ha.*	*Damages in roads Mts*
1996	169	2	-	3,289	1,357,295	258,487	-
1997	-	-	-	-	-	6,288	-
1998	-	-	-	-	-	1,252	-
1999	3	-	1	2	7,849	8,865	-
2000	347	725	708	7,244	3,305,582	561,147	545,194
2001	19	-	148	1,676	590,026	80,688	59,734
2002	11	-	37	1,373	960,321	49,878	24,122
2003	7	-	11	357	96,999	38,757	849
2004	2	3	-	-	8,430	51,543	3,180
2005	9	-	3	947	72,567	3,273	88,968
2006	15	1	130	824	807,202	22,027	75,161
2007	2	2	44	334	75,156	38,635	193,773
2008	4	-	-	-	43,601	7,133	3,322
2009	32	17	210	482	528,597	144,775	856,766
2010	11	8	90	94	141,813	51,186	590,638
2011	250	22	435	1,048	1,884,402	351,937	2,640,686*
2012	26		176	241	54,909	19,109	21,019
2013	184	11	252	1,103	1,893,178	205,185	1,874,467*
2014	40	1	141	5	337,143	9,522	41,838
2015	-	-	-	-	-	-	-
2016	2	-	-	3,590	48,235	20,668	6,785
2017	17	-	7	8,703	61,323	21,158	142,846
2018	63	315	7	295	701,775	70,335	566,410
2019	30	8	1	203	496,684	37,920	520,979
TOTAL	**1,243**	**1,115**	**2,401**	**31,810**	**13,473,087**	**2,059,768**	**8,256,737**

Source: NCDM (2023)

4.3 Existing Relevant Frameworks, Approaches, Methods and Tools

FEMA (2001) has developed HAZUS framework with a clear objective which is try to facilitate loss estimation, a vital component in decision-making processes across all levels of government. HAZUS serves as the foundation for crafting mitigation plans, policy development, emergency preparedness, and response and recovery planning. The direct loss module assesses damages incurred by buildings and infrastructure. These direct loss figures are then transformed into measurements of functionality loss for each sector, subsequently becoming input data for the indirect loss module. Notably, HAZUS employs a dynamic input-output model algorithm for its loss estimation approach. The assessment process delineated is designed for inundation hazards but possesses generic applicability to other hazards with minor modifications. Costa et al. (2017) developed a cost assessment framework for adaptation, and it composed of 4 levels (Levels 1 to 4) and 5 phases (Phases 2 to 5). It covers a comprehensive approach for quantifying the costs of adaptation with each level and phase building upon the previous one. The framework assesses risks and vulnerability in Phase 2, identifies adaptation options in Phase 3, assesses and selects options in Phase 4, and plans and implements in Phase 5.

In the context of damage assessment using damage functions, two distinct approaches emerge: 'absolute damage' functions, quantifying direct monetary losses based on flood depth, and 'relative damage' functions, expressing damage as a percentage of the maximum potential loss for specific land-use categories[1]. Absolute damage functions, rooted in historical flood surveys and land use data, offer specificity but require region-specific derivation. Conversely, relative damage functions, calculated by juxtaposing asset values with potential losses, present broader applicability but demand similarity in damage processes. The choice between these approaches depends on regional characteristics, data availability, and the need for precision in diverse geographic contexts, underscoring the nuanced considerations in selecting an appropriate methodology for comprehensive damage assessment.

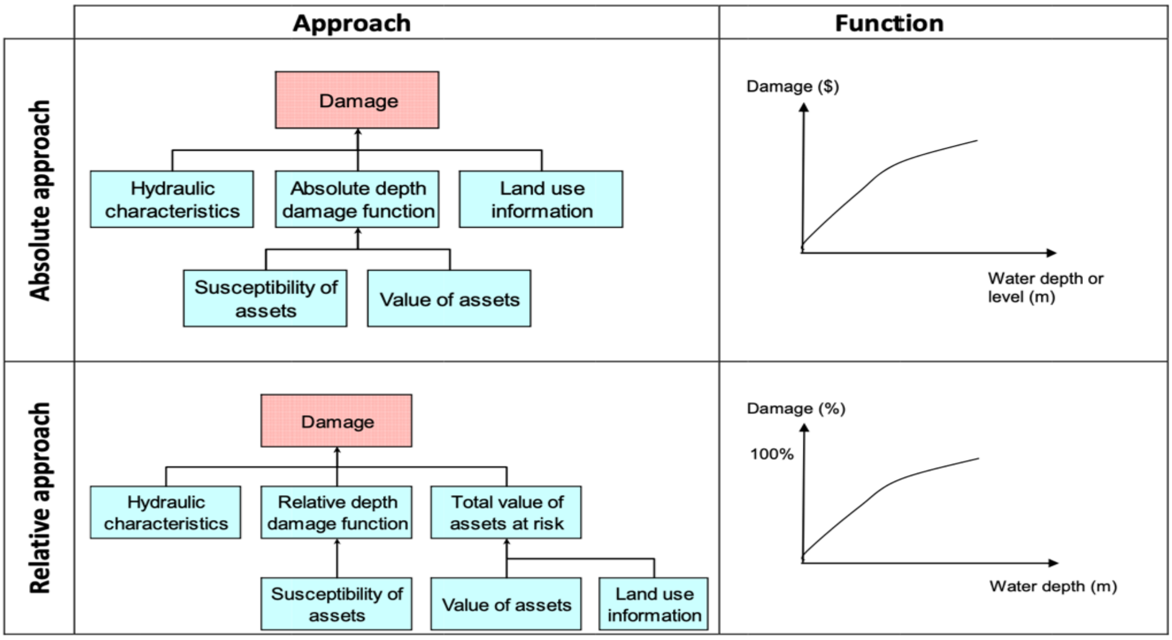


Figure 4: The Two-Damage Approach of Relative and Absolute
Source: MRC (2010)

ECLAC (2003) reported that Damage and Loss Assessment (DALA) is an important method and tool developed by the UN Economic Commission for Latin America in the 1970s, and served as a standardized tool for the monetary evaluation of disaster-induced damage

[1] Royal Haskoning, Deltares, UNESCO-IHE, The Flood Management and Mitigation Programme, 'Component 2: Structural Measures and Flood Proofing in the Lower Mekong Basin', May 2010, Final Report, Volume 3A "Best Practice Guidelines for Flood Risk Assessment", 158 pp.

(pertaining to physical assets, capital stock, and material goods) and losses (related to flows of goods and services, income, and costs) resulting from the temporary absence of destroyed assets. The DALA is instrumental in assessing the potential impact of disasters on national economic growth, the external sector, fiscal balances, as well as the repercussions on household or individual income and livelihoods due to the decline caused by disasters (De Groeve, T et al., 2013).

In flood loss assessment, two key concepts are stage–damage curves and unit losses (Jovel, R. J., & Mudahar, M., 2010). Stage–damage curves graphically depict the relationship between expected loss and varying floodwater depths, specifically assessing losses to structures. Deeper water correlates with more significant losses, ranging from damage to floor coverings and furniture at lower levels to complete loss of contents and structural endangerment at higher depths. These curves can be developed synthetically using data on building contents and repair costs or based on actual losses measured after flooding events. The unit loss approach involves calculating losses to individual properties, aggregated to estimate the total loss for the event, typically utilizing surveys, stage–damage curves, or average figures (Penning-Rowsell and Chatterton, 1977). Loss databases play a pivotal role in monitoring expenditures resulting from disasters and formulating strategies for disaster reduction. These databases serve multiple purposes, including disaster forensics and disaster risk assessments. Disaster forensics involves conducting studies to enhance understanding of the unfolding of a disaster, extracting valuable lessons from the experience. The information needed for these applications overlaps, with forensic and modelling applications requiring more detailed data. There are some studies on damage and loss estimation due to flooding and other hazards which are presented in Table below.

Table 3: Studies on Damage and Loss Estimation due to Flooding and other Hazards

	Studies	Key Findings	Case Studies	Scope and Limitations	Determination of Methods/Tools
1	Haberman and Hedel (2018)	Damage Functions - the magnitude of a natural hazard and average damage.	Impacts from coastal floods on roads, railways, and buildings in the United Kingdom	Several insurance companies have knowledge of damage estimations for critical infrastructure, but this knowledge is proprietary and inaccessible	Damage functions estimation
2	Vanneuville et al. (2003)	Critical infrastructure assets are resilient to flood hazard	Dender catchment is affecting floods in Flanders and Brussels in Belgium	DEM data requires altimetric precision of less than a decimeter	Estimated all linear structures, i.e., waterways, roads, and railroads using Landsat images
3	Noi, L et al (2021)	The assessment risk of six cities in the ASEAN region to CC given their location, exposure to sea level rise, storm surge, flooding, and salinity intrusion.	CC-related loss and damage assessments to urban transportation infrastructure in two cities of Cambodia (Kampot and Sihanoukville) as well as two cities each in Thailand and Vietnam	Road infrastructure was identified as being most at risk from the impacts of climate change. Flooding and SLR represent potential hazards as identified through the Rapid Vulnerability Analysis	Through analyses conducted using NK-GIAS software, economic losses for different flood scenarios were determined
4	M.A.U.R. Tariq, O.A.C. Hoes, and N.C. Van de Giesen (2014)	Insurance rates are based on historic flood events or a specific design flood. Expected annual damages developed to assess the spatial distribution of risk.	Development of a risk-based framework to integrate flood insurance.	Flood-warning system for this stretch is not very efficient.	Depth damage function for a variety of infrastructures Lists several GIS-based commercial software for flood damage and loss assessment
5	Chinowsky, Paul S er al (2015)	- Focuses on the physical asset of road infrastructure by evaluating the potential impact of changes from stressors - The mean additional cost of maintaining the same road network through 2050 amounts to US$10.5 billion.	Infrastructure and climate change: a study of impacts and adaptations in Malawi, Mozambique, and Zambia.	- Total Costs, Opportunity Costs, and Adaptive Advantage metrics are used. - Using these metrics, proactive adapt and re-active no-adapt approaches are evaluated	- For paved roads, the adaptation upgrades include a new binder, which is more resilient to increased pavement temperatures - For gravel roads, adaptation upgrades focus on protection from precipitation and flooding–an upgraded road is resurfaced with crushed gravel mix and a deeper road base is laid - For unpaved roads, the adaptation option is to upgrade unpaved (dirt) roads to an adapted gravel road - Costs of rebuilding inundated roads after a 1-meter sea level rise are shown in the study.

4.4 Discussions

The CAN is developed to support the capacity development process and identify key existing capacities and what additional capacities may be needed to achieve the objectives (UNDP, 2008; and Sum, 2008). It was found that concerned government staff have average capacity to strategy, system, and support knowledge and tools to conduct assessment of losses, damages and adaptation costing methods, while the capacity and knowledge on "skills and technical methods" remain limited. Capacity building as part of infrastructure development in Cambodia is critical in enhancing economic performance and productivity. Unfortunately, JICA (2023) identify that MRD has very limited experience in maintaining and managing DBST, and its maintenance capacity is not high. Our findings indicate that there are several developed methods and tools for loss and damage assessment on road infrastructure due to climate change. The development of methods and tools is still limited in Cambodia, while availability of data from physical recorded remains narrows. With limitation of physical data, spatial data and analysis using ArcGIS and Google Earth Engine is perhaps most suited to Cambodia. Similarly, Hawchar et al. (2020) presents a GIS-based approach for the assessment of the impacts of climate change on critical infrastructure (CI) networks, and the approach uses high-resolution climate change projection maps and is easy to implement, making it valuable for infrastructure owners, state bodies, and local authorities to plan for potential impacts and identify risk hotspots. The framework provides a simple and flexible resource for developing an understanding of cross-sectoral risk and potential CI interdependencies and highlights key impactors, such as fluvial flooding, coastal flooding and erosion, sea level rise, and extreme wind speed events. Spatial analysis method is particular useful for high-level national climate change risk assessment in developing countries, where the detailed physical assessment may not have taken place.

Getting into detailed of the assessment, there are two statistical tools available for assessing damage and loss of climate change on road infrastructures. Firstly, **Depth-damage curve:** show the vulnerability of elements exposed to risk and can be expressed as absolute or relative terms. They plot the relationship between flood depth and expected damage to assets, providing a quantitative evaluation of flood risk. The results from depth-damage curves can inform flood management, mitigation plans, evaluation of flood protection measures, and estimation of damage costs for insurance and compensation purposes. They play a crucial role in flood risk management decision making. Depth damage curves utilise a methodology with flood damage assessment for flood depth–damage curves, which essentially serve as graphical representations showcasing how varying levels of flood depths correspond to different extents of damage (Martínez-Gomariz et al., 2020). Secondly, **Damage function:** Catastrophe models use damage functions to translate hazard intensity (e.g., shaking, wind, water) to a damage ratio, the repair cost of a building divided by its replacement value. While hazard information is plentiful, data for damage functions is limited, as seen in the damage function and risk range for coastal flooding and storms in Lisbon, Portugal. On the other hand, assessing damage and loss due to flooding is a critical aspect of flood management, yet it presents significant challenges due to its complexity, involving vast amounts of data, various types of damage, and considerations of spatial and temporal scales (Menoni et al., 2016). In case of flood analysis, the utilisation of remote sensing and geospatial tools has proven to be instrumental in advancing the understanding of flood events. A noteworthy contribution to this case is the Floodwater Depth Estimation Tool implemented in Google Earth Engine (FwDET-GEE) (Peter et al., 2020). This tool presents a robust solution for rapid and large-scale flood analysis, offering valuable insights into flood water depth estimation. Numerous studies have attempted to develop loss and damage assessment and map flood extents in areas affected by floods using

Sentinel-1 SAR data (Plank S, 2014; Twelefou et al., 2015; Tavus et al., 2018; Olen and Bookhegen, 2018; Ahmed and Kranthi, 2018).

5. CONCLUSIONS

For capacity needs, majority of concerned officials have average capacity to strategy, system, and support knowledge and tools to conduct evaluation and assessment of losses, damages and adaptation costing. Consequently, staff have limited capacity and knowledge on "skills and technical methods" to the adaptation costing model and how it could be used for building adaptation and resilience on road and its related infrastructures development. The study explores existing methods, including UNESCAP's framework emphasizing the assessment of risk, losses, and future projections through downscaling climate scenarios. Additionally, the research reviews a comprehensive cost assessment framework for adaptation, incorporating various aspects such as economic and non-economic losses, providing valuable insights for Cambodia's road infrastructure resilience. The development of methodologies and tools for assessing losses and damages in the road infrastructure projects has been a priority for the study derived from the findings of the review, which considers multiple factors such as the cost of damage, a multi-sector approach, and flood impact assessment in its damage estimation process. The review highlights challenges in assessing loss and damage, where losses are predominantly monetary, reflecting economic impacts from asset destruction, while damage includes both monetary and non-monetary consequences. The paper has several limitations and challenges which must be taken into consideration. For the existing assessment methodologies and tools for quantifying climate change-induced loss and damage are based on findings from literature reviews. While these reviews provide valuable insights into the concepts of loss and damage, the generalizability of the findings may be limited. Literature reviews are subject to the availability and scope of existing research, which may not encompass all relevant factors specific to Cambodia's road infrastructure.

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Policy Preference Analysis for Investment in Electric Vehicle Infrastructure Development

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ABSTRACT

The world has been clearly moving towards the electric vehicle (EV) transition since 2015 when the Paris Agreement was formed. The shift towards an EV-based society aligns with Sustainable Development Goal 7 (SDG 7), which focuses on ensuring sustainable and modern energy. Globally, supportive policies have been formulated for EV, such as investments in manufacturing, development of charging infrastructure, establishment of safety standards, promotion of technology adoption, and reduction of greenhouse gas (GHG) emissions. Therefore, the direction and decisions made in policy can significantly influence the long-term implementation and success of EV adoption. This research aims to analyze the influencing factors of electric vehicle policy formulation using Fuzzy Analytic Hierarchy Process (FAHP) and identify the most preferable EV alternative to develop under these factors using the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). The questionnaire data used in the analysis is based on knowledge and judgments of the experts working in the relevant fields. The analysis demonstrates that policy development can be divided into three phases which are short-term, mid-term and long-term depending on the priority of influencing factors. The result reveals that the policy could be formulated according to Operational Safety, Value for Money, Value for Engineering, Technology Adoption and Reduction of GHG respectively. The most potential EV to develop is Battery Electric Vehicle (BEV) followed by Fuel cell Electric Vehicle (FCEV), Plug-in Hybrid Electric Vehicle (PHEV) and Hybrid Electric Vehicle (HEV).

Keywords: Electric Vehicle, Policy Preference, FAHP, TOPSIS

1. INTRODUCTION

The global electric vehicle (EV) industry is experiencing rapid growth, with market competition for EV increasing significantly in 2023 and gaining acceptance in the transportation sector (International Energy Agency, 2023). The transportation sector relies heavily on oil as the primary fuel source for various vehicle types, including passenger cars (Ministry of Energy, 2022). The increasing demand for fuel in cars has led to a rise in GHG emissions, causing climate change (Intergovernmental Panel on Climate Change, 2014). To address this, countries worldwide are developing EV and transitioning to clean energy in line with the United Nations' Sustainable Development Goals (SDGs) Goal 7 (United Nations, 2022). Currently, Thailand is developing policy under the concept of "Energy Transition" to shift the automotive industry from internal combustion engine vehicles (ICEV) towards EV based society, as outlined in the 20-year National Strategy (Office of the National Economic and Social Development Council, 2018). The focus is on the development of EV-related transportation infrastructure, following the 20-year Thai Transportation Development Strategy (Ministry of Transport, 2019), which aligns with the National Strategy.

The transition from traditional fuel sources can be achieved through various methods, including hybrid energy, fully electric energy, alternative energy (fuel cells), and powertrain technology development (Wilberforce et al., 2017). However, EV investment and development involves unforeseen risks, such as vehicle technology, batteries advancement, and smart grid infrastructure, which significantly impact energy costs and long-term implementation (Capuder, Miloš Sprčić, Zoričić, & Pandžić, 2020). Determining the investment guidelines for developing EV infrastructure is crucial, investment policies that benefit the economy and society include investing in charging stations, using applications, promoting safety, and building confidence. These decisions are complex and involve multiple stakeholders. The risk management can be achieved by analyzing factors that influence EV development and prioritizing the most preferable EV alternatives to determine the direction of the transportation sector under economic, environmental, and social sustainability aspects (Samaie, Javadi, Meyar-Naimi, & Feshki-Farahani, 2020).

The recent establishment of EV types consists of four main categories. 1.HEV, which combines an internal combustion engine with an electric motor and battery for improved fuel efficiency, primarily relying on regenerative braking for battery charging (Li et al., 2017). 2. PHEV, developed version of HEV with larger batteries that can be externally charged, allowing for limited all-electric range before switching to the gasoline engine (Martinez et al., 2017). 3. BEV, which operates fully on electricity stored in a battery pack, resulting in zero GHG emissions (Li et al., 2017). 4. FCEV, which utilizes hydrogen gas and a fuel cell to generate electricity, with water as the only byproduct, offering long driving ranges, quick refueling times but high in fuel cost (Cano et al., 2018).

2. RESEARCH OBJECTIVES

This research aims to analyze the influencing factors of policy preference for investment in EV infrastructure development using Fuzzy Analytic Hierarchy Process (FAHP) and identify the most preferable EV alternative to develop under the factors using the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS).

3. MATERIAL AND METHODS

3.1 Problem Definition, Objective Identification and Literature Review

To identify the objectives, influencing factors, and preferable alternatives for EV development, comprehensive literature reviews were conducted, examining research on Multi-Criteria Decision Making (MCDM), Analytic Hierarchy Process (AHP), Fuzzy Set Theory, Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), EV influencing factors, and diverse EV models. The development of appropriate EV policies could be guided by the analysis results. While the organizations involved in policy decision-making are taken into account, consumer perspectives have been overlooked. This is because relying solely on analysis from potentially inexperienced individuals might lead to misleading outcomes.

3.2 Research Framework

Upon completing the literature review, the influencing factors and potential EV alternatives were identified and organized within the 3 levels of AHP structure, First-level hierarchy (Goal), Second-level hierarchy (Influencing Factors) and Third-level hierarchy (Alternatives), refer to Figure 1. To gather expert opinions on these factors, a questionnaire was developed and distributed to experts working in the relevant fields. The collected data was then subjected to Fuzzy AHP (FAHP) analysis to determine the weight of each influencing factor, which would subsequently be used as criteria weights in the evaluation of EV alternatives using TOPSIS method, refer to Figure 2.

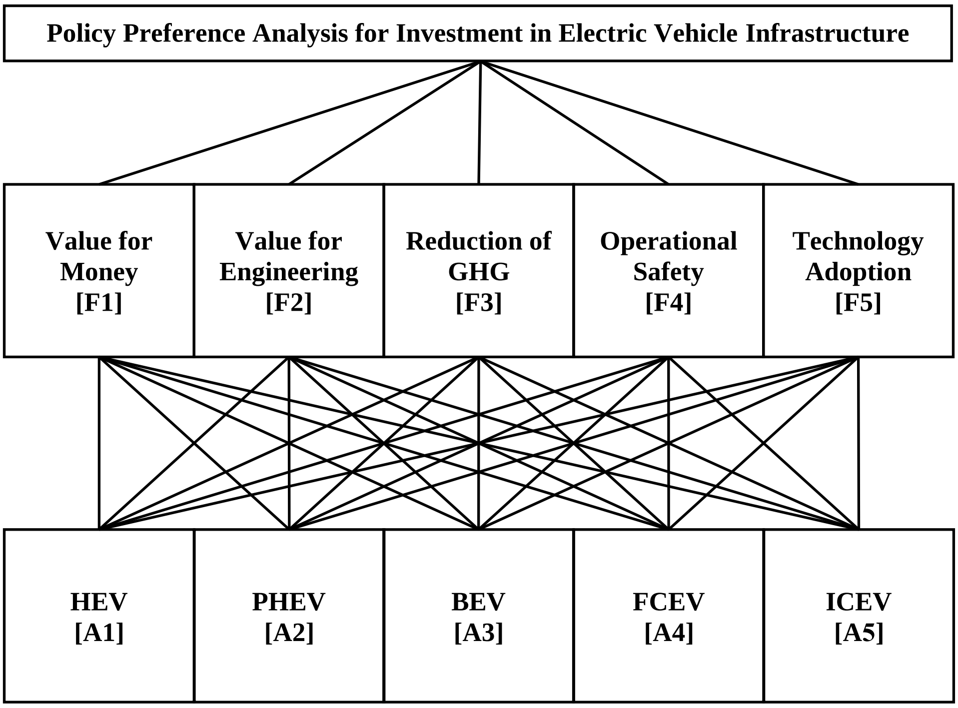

Figure 1 The structure for selecting preferable EV models under influencing factors.

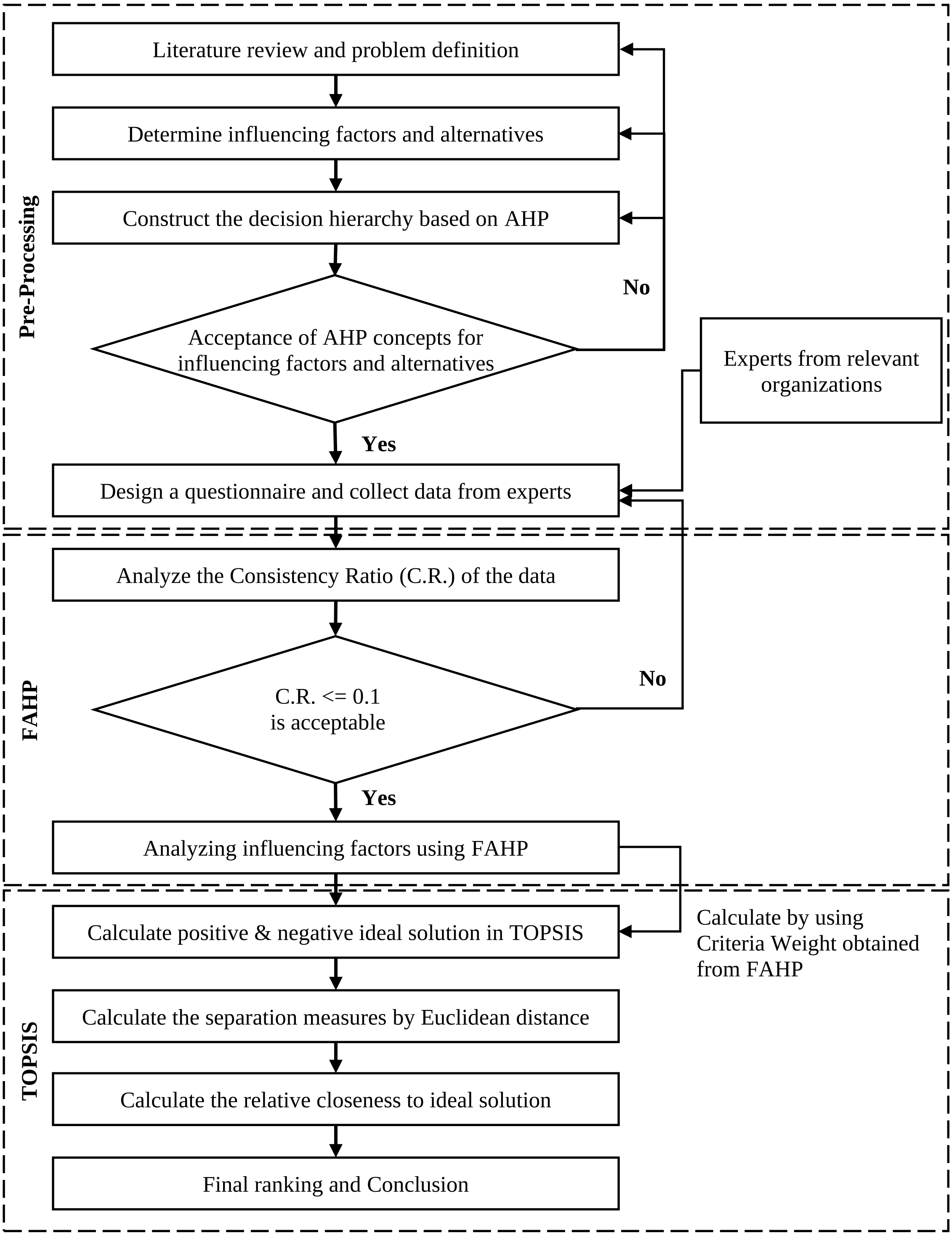

Figure 2 The FAHP-TOPSIS Framework.

3.3 Analytic Hierarchy Process (AHP)

The Analytic Hierarchy Process (AHP) is a structured methodology used for decision-making, breaking down problems into a hierarchy of goals, influencing factors, and alternatives. At each level, pairwise comparisons quantify the relative importance of elements using a scale of 1 to 9 to prioritize weights for each factor. The Consistency Index (C.I.) measures the deviation of these comparisons from perfect consistency, while the Consistency

Ratio (C.R.) compares it to random judgments, with a C.R. of 0.1 or less being acceptable. Ensuring consistency is crucial for the validity of AHP results, as it reflects the accuracy of the derived priorities (Saaty & Vargas, 2012).

First-level hierarchy (Goal)

The top level of the hierarchy, representing the goal or objective of the decision-making process. The objective of this research is to analyze the policy preference analysis for investment in electric vehicle infrastructure development.

Second-level hierarchy (Influencing Factors)

This level consists of the main influencing factors that will be used to evaluate the alternatives as listed below,

i. Value for Money [F1]: all related costs such as maintenance, investment, vehicles, battery, fuel and electricity. (Murugan & Marisamynathan, 2022)

ii. Value for Engineering [F2]: advancement of battery, charging infrastructure, manufacturing facilities, relevant mobile applications and vehicle models. (Ahmad et al., 2017)

iii. Reduction of Greenhouse Gas [F3]: the major method to solve the Global Warming crisis through the emission mitigation of Carbon dioxide (CO2), Methane (CH4), Nitrous oxide (N2O) and industrial gases. (Kim et al., 2020)

iv. Operational Safety [F4]: driver education, battery fire prevention, post-crash safety, charging safety and manufacturer standards. (Hu, Huang, Bai, Wang, & Qi, 2021)

v. Technology Adoption [F5]: policy understanding, technology acknowledgment, charging behavior, infrastructure availability, life quality and brand reputation. (Bobeth & Matthies, 2017)

Third-level hierarchy (Alternatives)

The bottom level of the hierarchy, representing the potential EV models to be developed under the influencing factors. The potential EV models for this research are HEV, PHEV, BEV, FCEV and ICEV

3.4 Fuzzy Set Theory application on AHP (FAHP)

The use of fuzzy logic allows researchers to calculate uncertain data obtained from decision-makers. Therefore, the importance between factors should be analyzed using the Fuzzy Analytic Hierarchy Process (FAHP) to determine the weights of influencing factors.

The analysis of data using the FAHP method involves using triangular fuzzy numbers (TFNs) instead of single numbers 1-9 at $\delta = 0.75$ (moderate fuzzy area), refer to Table 1. This is done by creating a fuzzy number pattern in the form of (l, m, u), where m is the middle value and l & u are the lower and upper bound values respectively. Triangular fuzzy numbers can now be constructed and represented (Buckley & Eslami, 2002), refer to Figure 3.

Table 1 Linguistic terms and Triangular Fuzzy Numbers.

Linguistic Scale	**AHP Scale**	**Triangular Fuzzy Scale**	**Triangular Fuzzy Reciprocal Scale**
Equal importance	1	(0.25, 1, 1.75)	0.57, 1, 4
Weak or slight	2	(1.25, 2, 2.75)	0.36, 0.5, 0.80
Moderate importance	3	(2.25, 3, 3.75)	0.27, 0.33, 0.44
Moderate plus	4	(3.25, 4, 4.75)	0.21, 0.25, 0.31
Strong importance	5	(4.25, 5, 5.75)	0.17, 0.20, 0.24
Strong plus	6	(5.25, 6, 6.75)	0.15, 0.17, 0.19
Very strong importance	7	(6.25, 7, 7.75)	0.13, 0.14, 0.16
Very strong plus	8	(7.25, 8, 8.75)	0.11, 0.13, 0.14
Extremely strong	9	(8.25, 9, 9.75)	0.10, 0.11, 0.12

(Modified from Saaty, 2012)

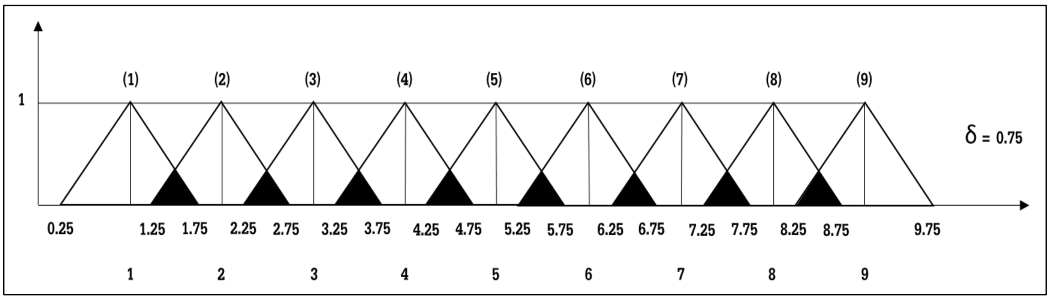

Figure 3 Triangular fuzzy number diagram.
(Modified from Buckley, J., 2022)

3.5 Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)

The relative closeness of alternatives is analyzed using the TOPSIS technique to establish a ranking order. This process involves identifying alternatives that have the Euclidean distance nearest to the positive ideal solution, A+ and farthest from the negative ideal solution, A- for each pairwise influencing factors, refer to Figure 4. This evaluation of relative closeness aids in prioritizing alternatives and determining the most preferable model for EV to be developed under the range of influencing factors. (Hwang & Yoon, 1981)

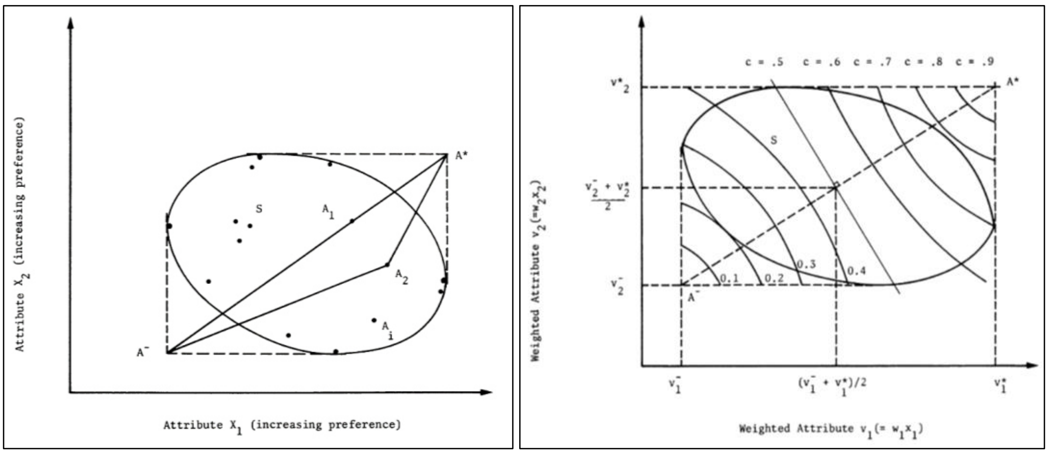

Figure 4 Euclidean distance to the positive and negative ideal solutions in two-dimensional space.
(Hwang & Yoon, 1981)

4. RESULTS

A total of 45 experts were invited to participate in the research study. The pairwise questionnaires were distributed to collect data and preliminary analysis using AHP method on 5 influencing factors, refer to Figure 5. These experts were then categorized into 3 groups based on their areas of specialization, consisting of the following, refer Figure 6.

1. EV Manufacturers e.g. Related private companies.
2. EV Infrastructure Developers e.g. Petroleum Authority of Thailand (PTT), Provincial Electricity Authority (PEA) and Electricity Generating Authority of Thailand (EGAT).
3. Policy Makers e.g. Department of Highways (DOH), Department of Rural Roads (DRR), Department of Land Transport (DLT), Office of the National Economics and Social Development Council (NESDC), Department of Public Works and Town & Country Planning (DPT) and related consultant organizations.

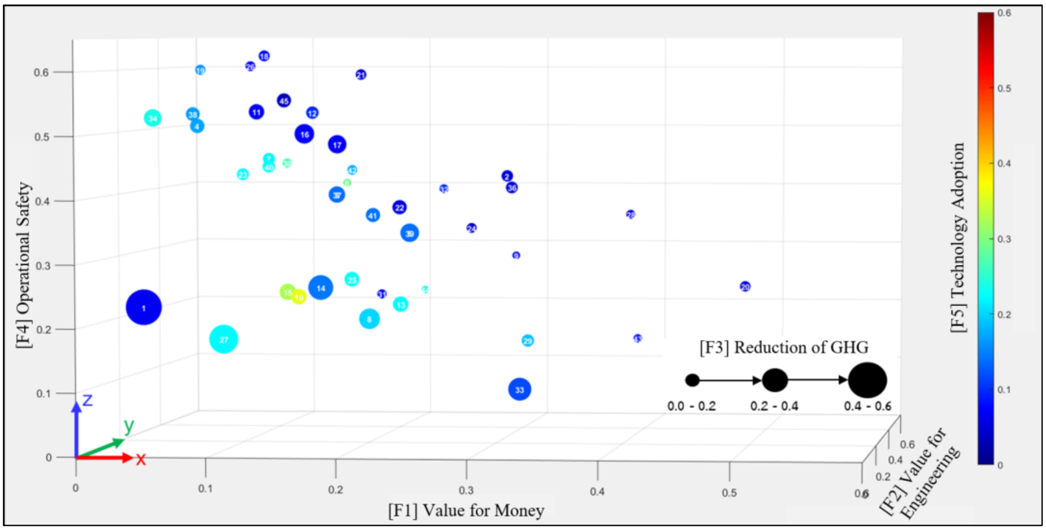

Figure 5 The result of influencing factor analysis using AHP.

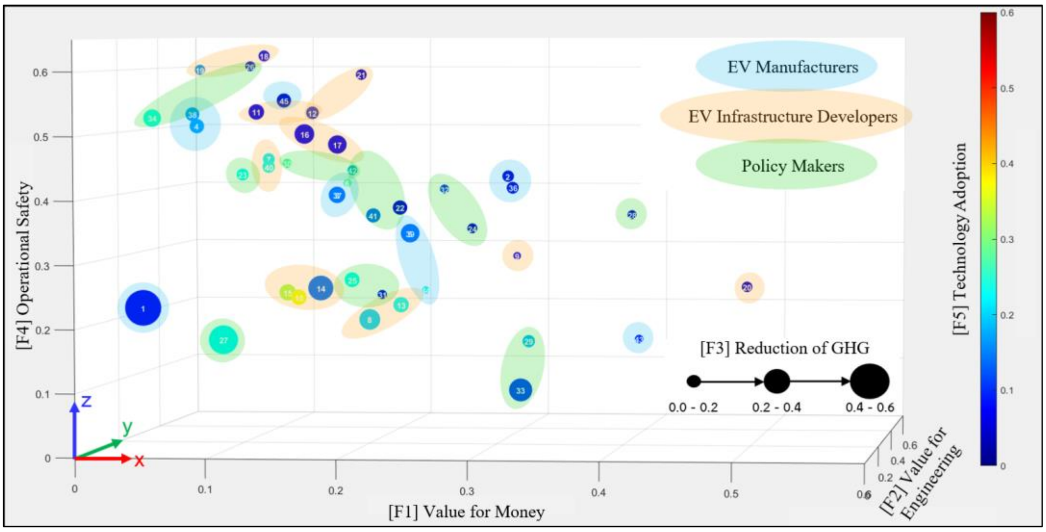

Figure 6 The result of influencing factor analysis categorized by decision makers.

4.1 AHP Influencing Factors Result

The average weight of influencing factors analysis among the experts using AHP are Operational Safety (0.377), Value for Money (0.197), Value for Engineering (0.169), Technology Adoption (0.144) and Reduction of GHG (0.112) respectively, refer to Table 2.

Table 2 Influencing factors weights analysis using AHP.

Experts	[F1]	[F2]	[F3]	[F4]	[F5]
1	0.042	0.067	0.597	0.229	0.066
2	0.316	0.139	0.062	0.434	0.049
3	0.181	0.151	0.126	0.403	0.139
…	…	…	…	…	…
45	0.135	0.183	0.094	0.552	0.036
Geometric Mean	0.197	0.169	0.112	0.377	0.144

4.2 FAHP Influencing Factors Result

The average weight of influencing factors analysis among the experts using FAHP are Operational Safety (0.390), Value for Money (0.248), Value for Engineering (0.189), Technology Adoption (0.087) and Reduction of GHG (0.086) respectively, refer to Table 3. The integration of Fuzzy set theory with AHP analysis resulted in more refined value compared to prior AHP result, refer to Figure 7.

Table 3 Influencing factors weights analysis using FAHP.

Experts	[F1]	[F2]	[F3]	[F4]	[F5]
1	0.000	0.000	1.000	0.000	0.000
2	0.372	0.162	0.000	0.465	0.000
3	0.191	0.182	0.166	0.277	0.185
…	…	…	…	…	…
45	0.101	0.254	0.085	0.560	0.000
Geometric Mean	0.248	0.189	0.086	0.390	0.087

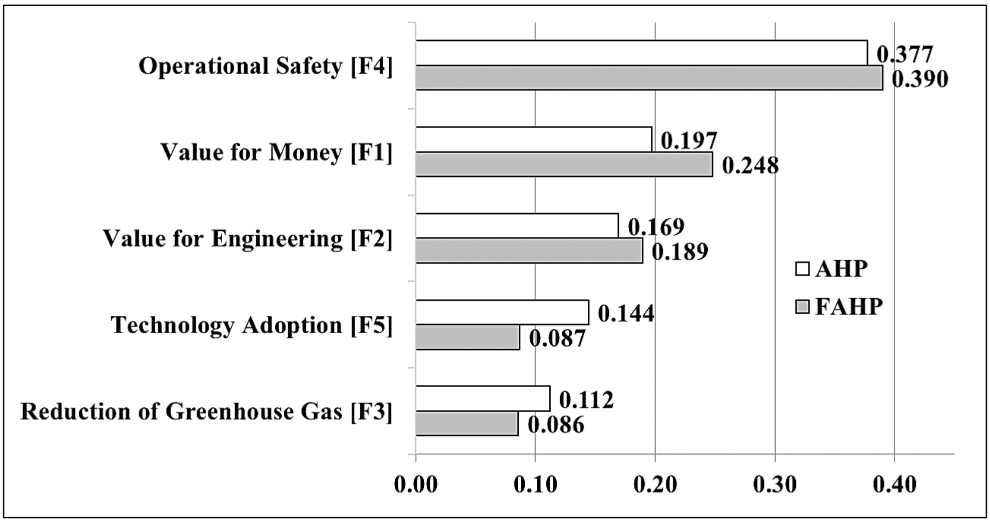

Figure 7 The comparison of influencing weights between AHP and FAHP analysis.

4.3 TOPSIS Potential EV to Develop Result

The average relative closeness of EV alternatives analysis using TOPSIS are BEV (0.737), FCEV (0.605), PHEV (0.579), HEV (0.505) and ICEV (0.078) respectively, refer to Table 4 and Figure 8.

Table 4 The relative closeness of alternatives using TOPSIS.

Experts	HEV	PHEV	BEV	FCEV	ICEV
1	0.000	1.000	1.000	1.000	0.088
2	0.000	0.824	0.824	0.000	0.099
3	0.370	0.670	1.000	0.598	0.080
…	…	…	…	…	…
45	0.212	0.408	0.665	0.788	0.096
Geometric Mean	0.505	0.579	0.737	0.605	0.078

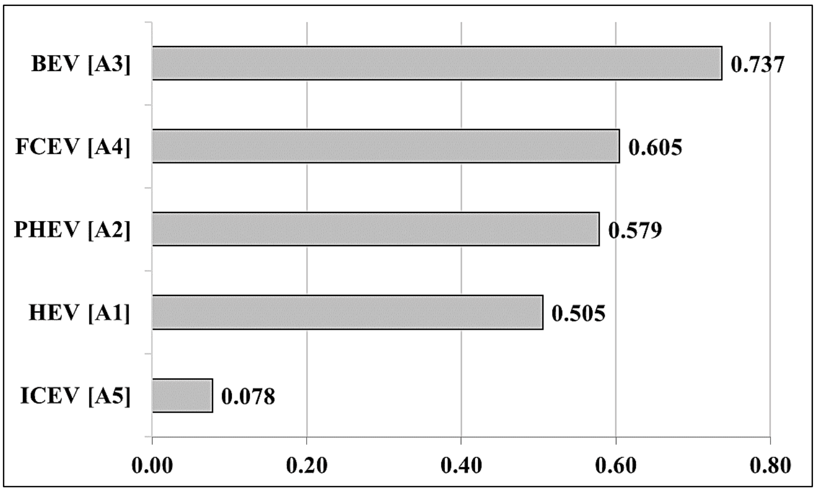

Figure 8 The relative closeness of alternatives using TOPSIS.

4.4 FAHP Result categorized by groups

As shown in Table 5 and Figure 9, the result of the influencing factors is as outlined.

For EV Manufacturers, the most important factor is Operational Safety (0.377), followed by Value for Money (0.288), Value for Engineering (0.244), Reduction of GHG (0.073) and Technology Adoption (0.019) respectively.

For EV Infrastructure Developers, the most important factor is Operational Safety (0.417), followed by Value for Money (0.221), Technology Adoption (0.157), Value for Engineering (0.125), Reduction of GHG (0.079) and respectively.

For Policy Makers, the most important factor is Operational Safety (0.372), followed by Value for Money (0.233), Value for Engineering (0.202), Reduction of GHG (0.109) and Technology Adoption (0.084) respectively.

Table 5 Influencing factors weights categorized by roles of decision makers.

Role of works	[F1]	[F2]	[F3]	[F4]	[F5]
EV Manufacturers	0.288	0.244	0.073	0.377	0.019
EV Infrastructure Developers	0.221	0.125	0.079	0.417	0.157
Policy Makers	0.233	0.202	0.109	0.372	0.084

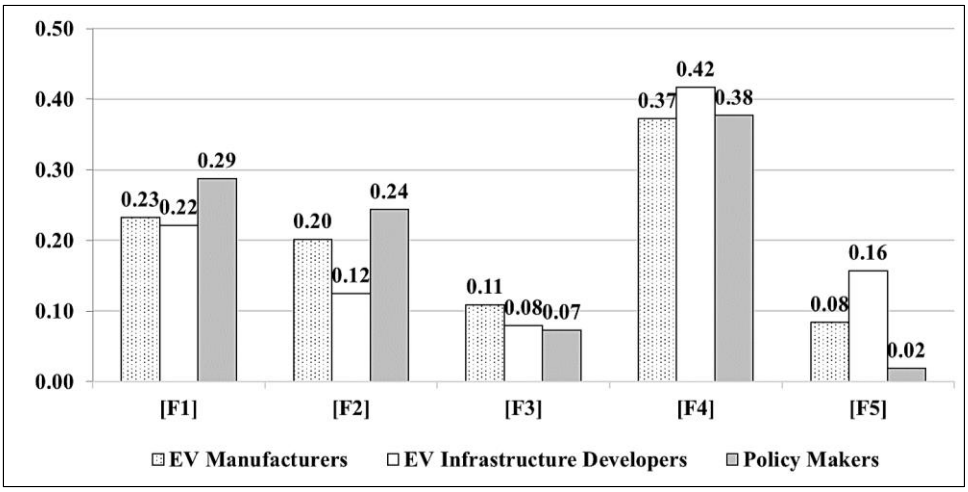

Figure 9 Influencing factors weights categorized by roles of decision maker.

4.5 TOPSIS Result categorized by groups

As shown in Table 6 and Figure 10, the result of the preferable alternative is outlined.

For EV Manufacturers, the most preferable alternative to develop under the influencing factors is BEV (0.623), followed by PHEV (0.584), FCEV (0.578), HEV (0.565) and ICEV (0.084) respectively.

For EV Infrastructure Developers, the most preferable alternative to develop under the influencing factors is BEV (0.732), followed by FCEV (0.601), HEV (0.586), PHEV (0.499) and ICEV (0.075) respectively.

For Policy Makers, the most preferable alternative to develop under the influencing factors is BEV (0.885), followed by PHEV (0.671), FCEV (0.643), HEV (0.333) and ICEV (0.075) respectively.

Table 6 The relative closeness of alternatives categorized by decision makers.

Role of works	HEV	PHEV	BEV	FCEV	ICEV
EV Manufacturers	0.565	0.584	0.623	0.578	0.084
EV Infrastructure Developers	0.586	0.499	0.732	0.601	0.075
Policy Makers	0.333	0.671	0.885	0.643	0.075

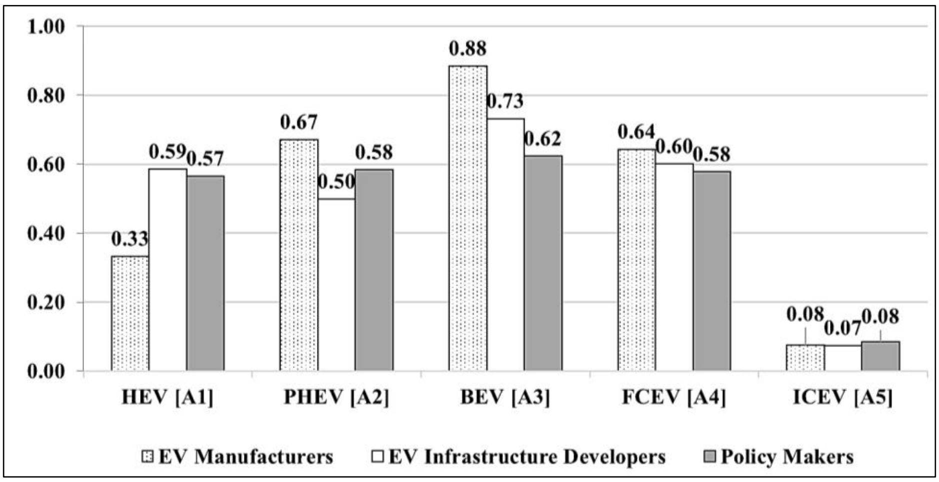

Figure 10 The relative closeness of alternatives categorized by decision makers.

4.6 Policy Result for Influencing Factors

According to the analysis of 5 influencing factors, the 31 possible scenarios to develop the policy can be formed, refer to Figure 11. The development focusing on the factors can be divided into 3 phases e.g. short-term, mid-term and long-term depending on the importance of the weight of each factor. The short-term development can be implemented immediately (aim to achieve a development on 1-2 factors), the mid-term development could be start when the short-term scenario is acceptable reached (aim to further achieve a development on 3-4 factors) and the long-term development will be done to cover all necessary factors needed for the EV infrastructure development (aim to achieve a development on 4-5 factors).

The influencing factor weights gaining from the analysis imply that the factors with the higher value such as Operational Safety (0.390) and Value for Money (0.248) are meant to be developed first, then the remaining factors such as Value for Engineering (0.189), Technology Adoption (0.087) and Reduction of GHG (0.086) should be planned to be achieved once the predecessor factors are practically implemented, refer to Figure 12.

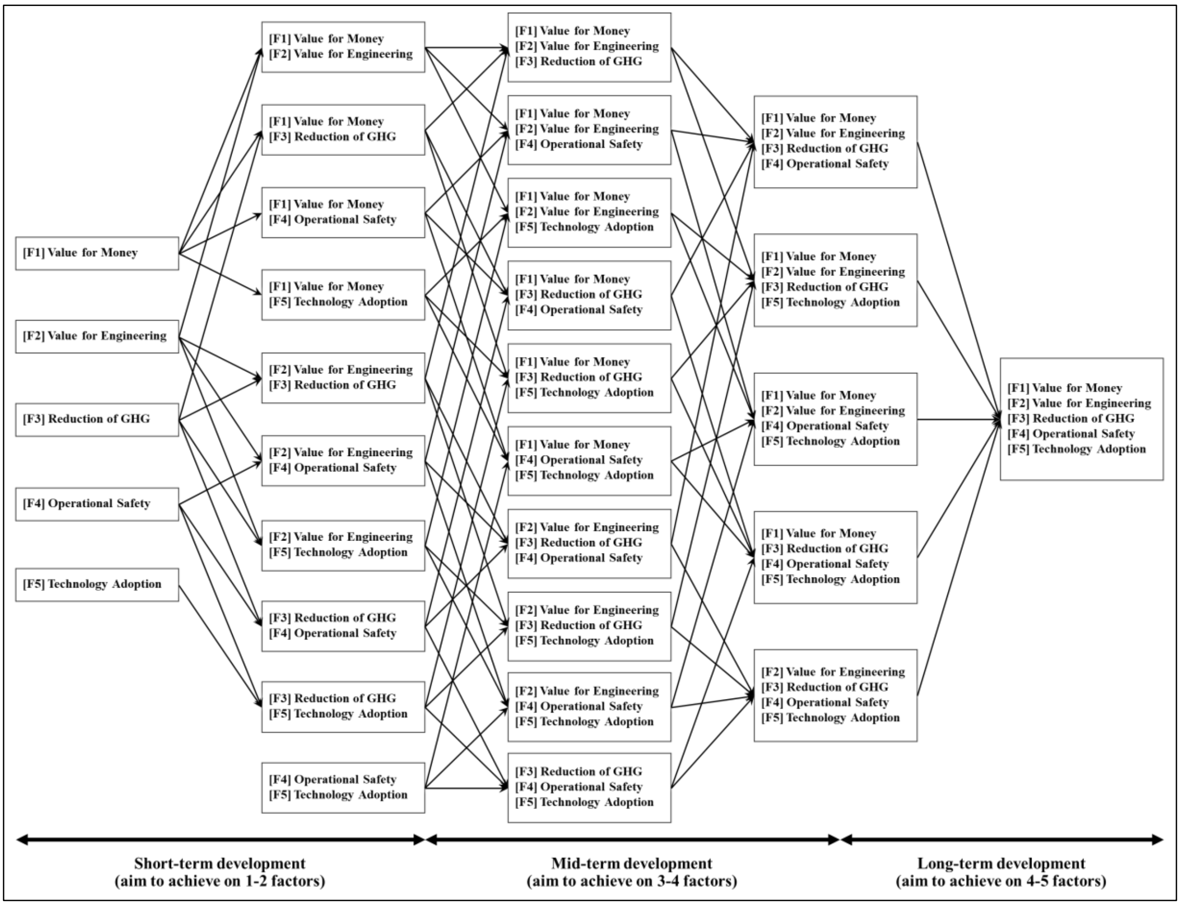

Figure 11 Policy development scenarios.

[F4] Operational Safety
[F1] Value for Money
→
[F4] Operational Safety
[F1] Value for Money
[F2] Value for Engineering
→
[F4] Operational Safety
[F1] Value for Money
[F2] Value for Engineering
[F5] Technology Adoption
→
[F4] Operational Safety
[F1] Value for Money
[F2] Value for Engineering
[F5] Technology Adoption
[F3] Reduction of GHG

Figure 12 Policy development implementation scenarios.

4.7 Policy Result for Preferable EV Alternatives under Influencing Factors

According to the TOPSIS principle, the most preferable alternative should be located nearest to the positive ideal solution and farthest from the negative ideal solution under the pairwise of influencing factors. The preference curves (i.e. Relative Closeness curve) were formed regarding the weight of influencing factor for each pairwise.

Preferable EV Alternatives under Influencing Factors [F1] and [F2]

Under the pairwise analysis between Value for Money and Value for Engineering, BEV is the most preferable alternative to be developed. An organization could consider both factors as the primary focus as they share the similar potential to boost preference for the alternatives, refer to Figure 13.

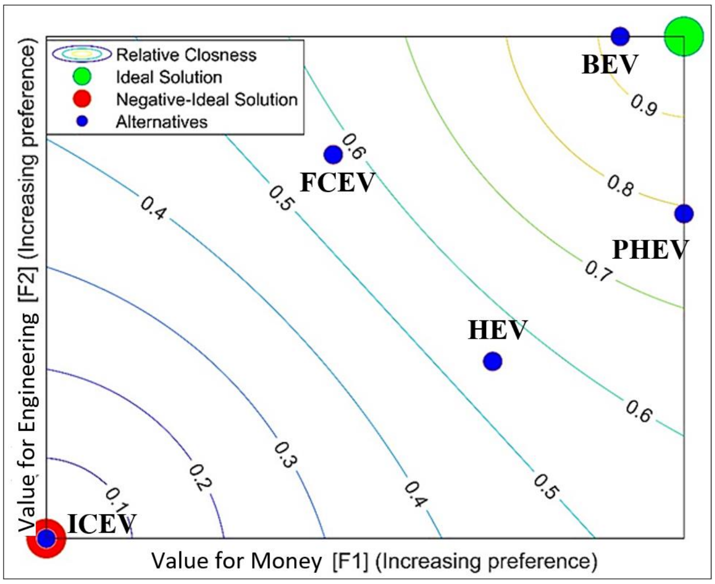

Figure 13 Preferable EV Alternatives under Influencing Factors [F1] and [F2].

Preferable EV Alternatives under Influencing Factors [F1] and [F3]

Under the pairwise analysis between Value for Money and Reduction of GHG, PHEV is the most preferable alternative to be developed. An organization should consider Value for Money as a primary focus as it has a stronger potential to boost preference for the alternatives, refer to Figure 14.

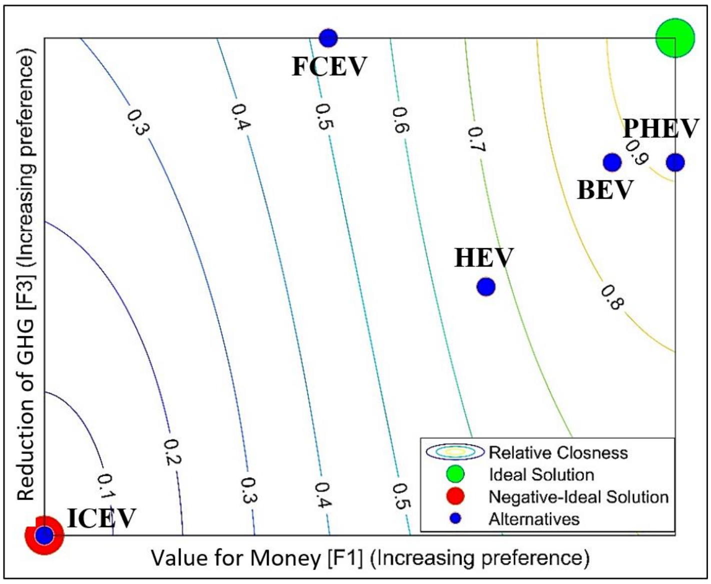

Figure 14 Preferable EV Alternatives under Influencing Factors [F1] and [F3].

Preferable EV Alternatives under Influencing Factors [F1] and [F4]

Under the pairwise analysis between Value for Money and Operational Safety, HEV is the most preferable alternative to be developed. An organization could consider Value for Money as a primary focus as it has a slightly stronger potential to boost preference for the alternatives, refer to Figure 15.

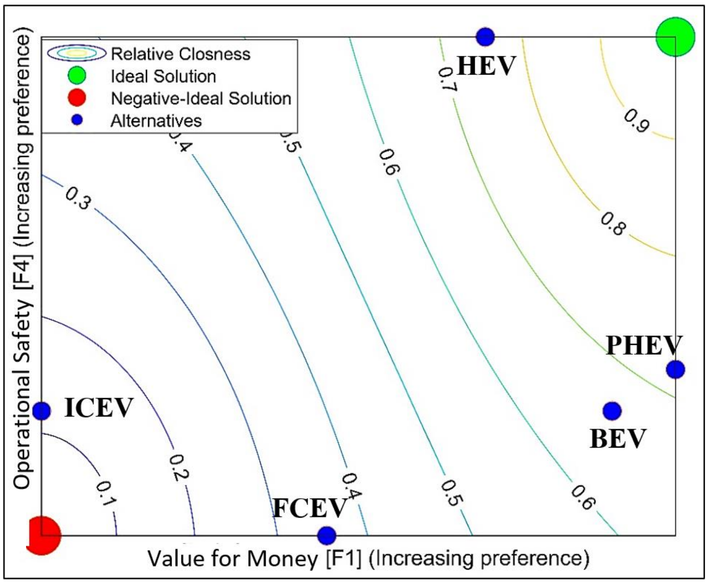

Figure 15 Preferable EV Alternatives under Influencing Factors [F1] and [F4].

Preferable EV Alternatives under Influencing Factors [F1] and [F5]

Under the pairwise analysis between Value for Money and Technology Adoption, BEV is the most preferable alternative to be developed. An organization should consider Value for Money as a primary focus as it has a stronger potential to boost preference for the alternatives, refer to Figure 16.

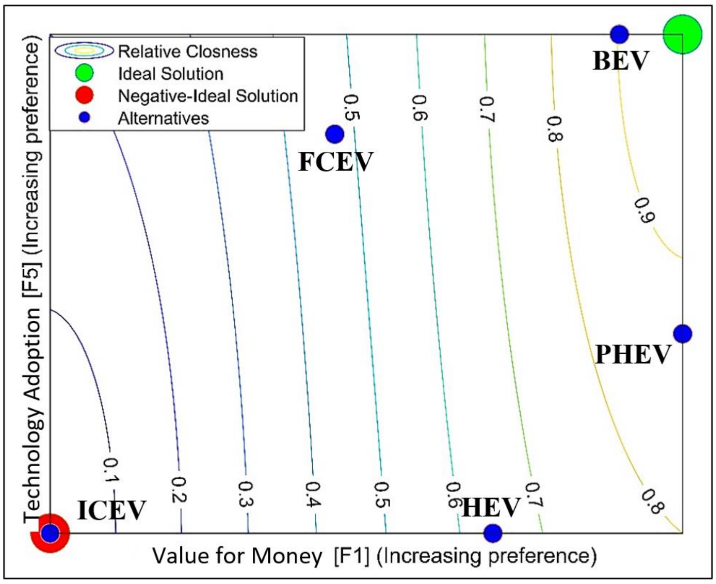

Figure 16 Preferable EV Alternatives under Influencing Factors [F1] and [F5].

Preferable EV Alternatives under Influencing Factors [F2] and [F3]

Under the pairwise analysis between Value for Engineering and Reduction of GHG, BEV is the most preferable alternative to be developed. An organization should consider Value for Engineering as a primary focus as it has a stronger potential to boost preference for the alternatives, refer to Figure 17.

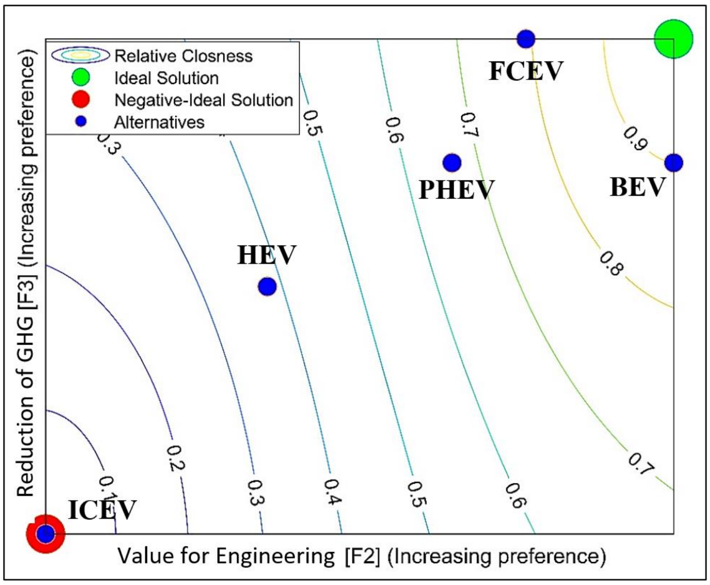

Figure 17 Preferable EV Alternatives under Influencing Factors [F2] and [F3].

Preferable EV Alternatives under Influencing Factors [F2] and [F4]

Under the pairwise analysis between Value for Engineering and Operational Safety, BEV is the most preferable alternative to be developed. An organization could consider both factors as the primary focus as they share the similar potential to boost preference for the alternatives, refer to Figure 18.

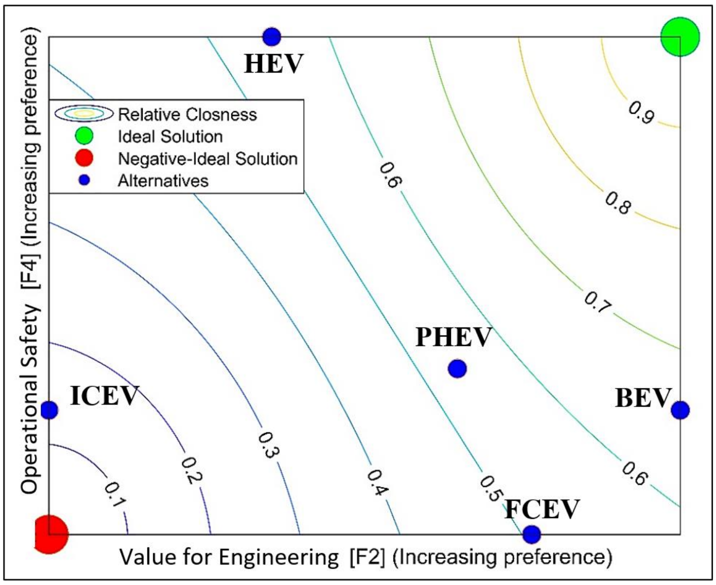

Figure 18 Preferable EV Alternatives under Influencing Factors [F2] and [F4].

Preferable EV Alternatives under Influencing Factors [F2] and [F5]

A Under the pairwise analysis between Value for Engineering and Technology Adoption, BEV is the most preferable alternative to be developed. An organization should consider Value for Engineering as a primary focus as it has a stronger potential to boost preference for the alternatives, refer to Figure 19.

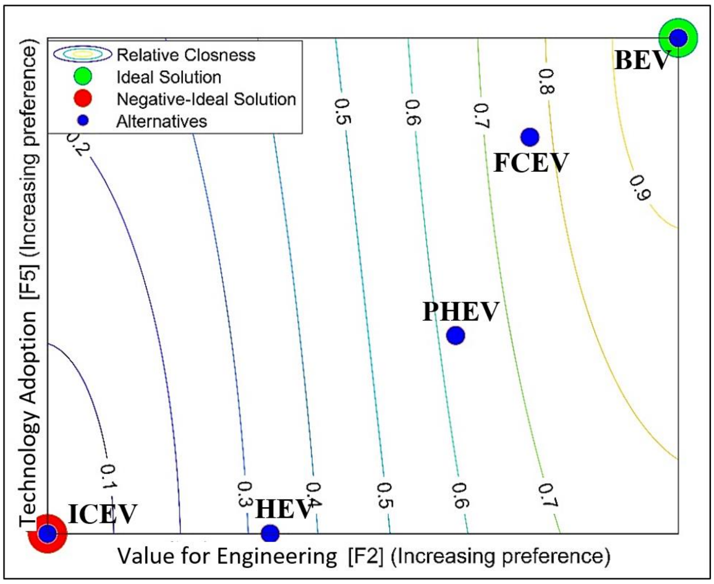

Figure 19 Preferable EV Alternatives under Influencing Factors [F2] and [F5].

Preferable EV Alternatives under Influencing Factors [F3] and [F4]

Under the pairwise analysis between Reduction of GHG and Operational Safety, HEV is the most preferable alternative to be developed. An organization should consider Operational Safety as a primary focus as it has a stronger potential to boost preference for the alternatives, refer to Figure 20.

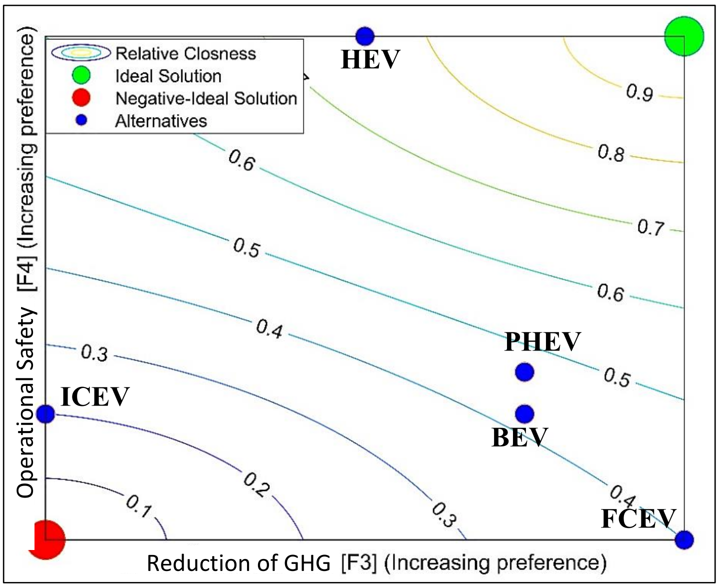

Figure 20 Preferable EV Alternatives under Influencing Factors [F3] and [F4].

Preferable EV Alternatives under Influencing Factors [F3] and [F5]

Under the pairwise analysis between Reduction of GHG and Technology Adoption, FCEV is the most preferable alternative to be developed. An organization should consider Reduction of GHG as a primary focus as it has a slightly stronger potential to boost preference for the alternatives, refer to Figure 21.

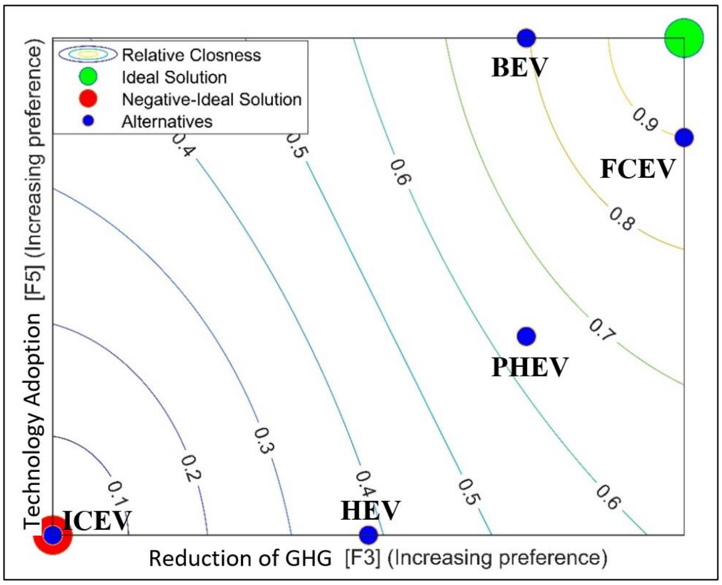

Figure 21 Preferable EV Alternatives under Influencing Factors [F3] and [F5].

Preferable EV Alternatives under Influencing Factors [F4] and [F5]

Under the pairwise analysis between Operational Safety and Technology Adoption, HEV is the most preferable alternative to be developed. An organization should consider Operational Safety as a primary focus as it has a stronger potential to boost preference for the alternatives, refer to Figure 22.

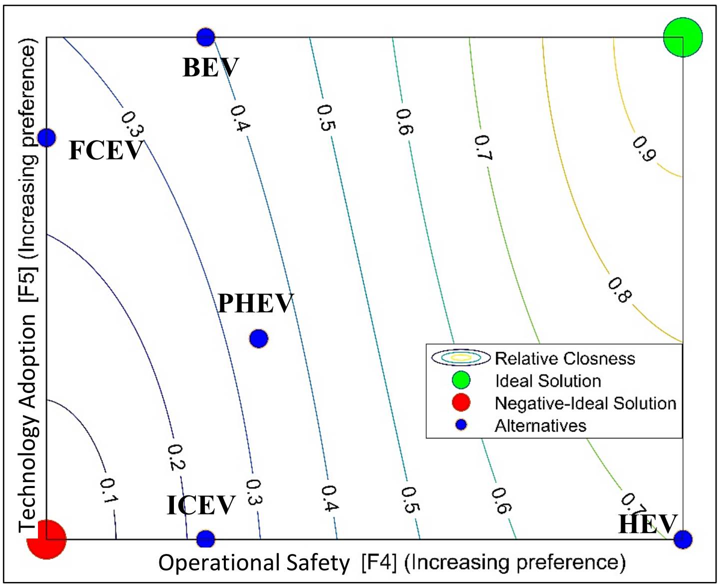

Figure 22 Preferable EV Alternatives under Influencing Factors [F4] and [F5].

5. CONCLUSIONS

This research analyzed the influencing factors of policy preference for investment in EV infrastructure development using FAHP and identified the most preferable EV alternative to develop under those factors using TOPSIS. The data used in the analysis was gathered from 45 experts who are working in relevant EV development and policy formation organizations, e.g., private EV manufacturing companies, PTT, PEA, EGAT, DOH, DRR, DLT, NESDC, DPT, and relevant consultant organizations.

The result illustrates that the most influencing factor is Operational Safety, followed by Value for Money, Value for Engineering, Technology Adoption, and Reduction of GHG, respectively. In parallel, the most preferable EV alternative to be developed under these influences is BEV, followed by FCEV, PHEV, and HEV, respectively.

As categorized by the group of experts, the results reveal that all groups concur that Operational Safety and Value for Money are the two most influencing factors for investment in EV infrastructure development. EV Manufacturers and Policy Makers share the view that the Value for Engineering factor ranks second in significance, while EV Infrastructure Developers lean towards Technology Adoption. Notably, the reduction of GHG provides the lower bound value among other factors.

For the preferable EV alternatives, all groups of experts have the same opinion that BEV is the most preferable alternative to be developed under those influencing factors. EV Manufacturers and Policy Makers share the view that PHEV is the secondary alternative, whereas EV Infrastructure Developers prioritize FCEV. Lastly, it is obvious that all groups prefer transitioning to electric-based vehicles since ICEV gets the lowest relative closeness in every aspect.

In conclusion, the findings of this research emphasize the importance of focusing on Operational Safety and Value for Money in EV development policies, as these factors significantly influence the successful adoption and integration of EVs into the transportation sector. The concerns related to charging infrastructure and affordability while promoting the environmental benefits of EVs are also crucial for creating comprehensive policies that promote the sustainable growth of the EV sector. The policymakers should focus on establishing promising safety regulations and standards while also considering cost-effective solutions for EV manufacturing and infrastructure development. Currently, BEV is the most reliable option, but it is also crucial to acknowledge the potential of FCEV in the long-term approach. The successful transition to an EV-based society provides a sustainable reduction of GHG emissions to mitigate the global warming crisis.

6. ACKNOWLEDGMENTS

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Engineering and Economic Analysis of Stone Mastic Asphalt for Rutting Resistance in Thailand

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ABSTRACT

Thailand's road network predominantly relies on Hot Mix Asphalt (HMA) with dense gradation, while Stone Mastic Asphalt (SMA) with gap gradation is favored in Europe for its superior performance. This study investigates the feasibility of adopting SMA with gap gradation in Thailand to address the challenges posed by high-traffic or heavy-load roads in a high-temperature climate. The research aims to compare the performance of HMA and SMA pavements. Additionally, a cost-effectiveness analysis is conducted to assess the economic viability of implementing SMA in Thailand's road construction projects. The findings will provide valuable insights into the suitability of SMA for Thailand's road construction, offering potential solutions to enhance road durability, safety, and cost efficiency in high-temperature environments.

While Thailand currently uses slag as the primary aggregate for Stone Mastic Asphalt (SMA), its limited availability presents a challenge. On the other hand, limestone, which is widely abundant and economically viable across the country, emerges as a viable candidate for this research. This study demonstrates the feasibility of using limestone as an aggregate for SMA and compares it with Conventional Mix Asphalt (CMA). The research results show that while SMA with PMA is 28.93% more expensive than CMA with AC40-50, its approximately 112.5% better rutting resistance makes it a more cost-effective choice in the long term.

Keywords: HMA, SMA, Rutting, Wheel-Tracking, Cost Effectiveness

1. INTRODUCTION

About 93% of Thailand's road network is composed of asphalt concrete, which faces a significant issue with rutting, posing a risk for road accidents. Stone Mastic Asphalt (SMA) stands out as a viable solution, classified as a 'Gap Grade' gradation type that enhances road surfaces' roughness, effectively improving rutting resistance. SMA is specifically designed to provide a durable, deformation-resistant pavement that can handle high traffic volumes and heavy loads effectively. Its unique gradation structure, with a higher coarse aggregate content contributes to its improved stability and resistance to rutting, making it a potential candidate for addressing the issues faced by Thailand's road network.

This study aims to explore the feasibility of adopting SMA in Thailand, focusing on its application to high-traffic and heavy-load roads in a high-temperature climate. Through laboratory testing, the performance of SMA were compared with that of Conventional Mix Asphalt.

Rutting resistance and permanent deformation will be assessed under simulated high-temperature conditions. Additionally, the study included a cost-effectiveness analysis to evaluate the economic implications of implementing SMA in Thailand's road construction projects.

The findings are expected to highlight the potential benefits of using SMA, including improved road durability, safety, and cost efficiency, ultimately contributing to the development of more resilient and long-lasting road networks in high-temperature environments.

2. Stone Mastic Asphalt (SMA)

SMA is an asphalt surfacing mix renowned for its exceptional rut resistance properties and superior durability compared to standard asphalt. It is essentially a gap-graded asphalt mix, primarily designed for surface courses, featuring a high proportion of coarse aggregate that interlocks to form a stone skeleton, resulting in significant voids or gaps between specific fractions of aggregate particles to resist permanent deformation.

This design predominantly incorporates a substantial portion of coarse aggregates, which contribute to the mixture's structural integrity and stability. The mix is infused with a mastic of bitumen and fillers, supplemented with fibers to ensure adequate stability to the binder and prevent drainage of the binder during transportation and placement. Stone-on-stone contact is ensured in this design, thereby enhancing the pavement's resistance to rutting and deformation under heavy traffic loads. These characteristics make SMA an ideal choice for high traffic highways.

The main benefits may be described as follows:

- high resistance to rutting (Richardson, 1999)
- high resistance to cracking
- high durability
- wear and raveling resistance
- insensitivity to water
- good skid resistance
- low surface noise
- superior surface finish

2.1 Comparing SMA and CMA

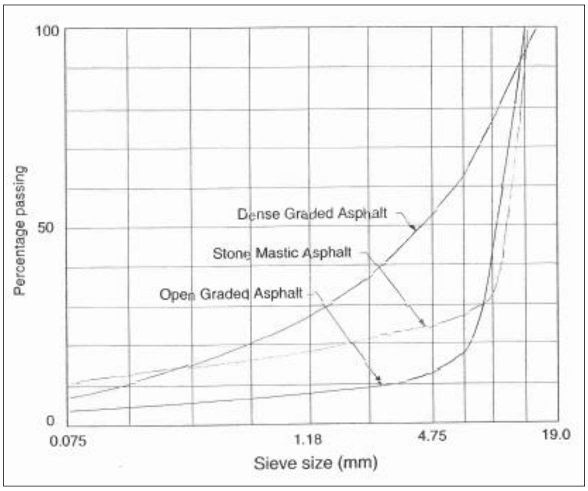

Figure 1 : Grading of different mix types
(AAPA, 2000)

Figure 1 shows the gradation in percent passing, Stone Mastic Asphalt (SMA) contains some medium or small-sized stones missing compared to Dense Graded Asphalt or Conventional Mix Asphalt (CMA). Despite this, there is still little air space between the aggregate particles, allowing for more direct contact between large and medium-sized particles. This structure of the coarse aggregate (Coarse Aggregate Skeleton) enables it to transmit or transfer loads from traffic into the road structure layer.

Figure 2 : Physical characteristics of SMA vs Conventional Mix Asphalt

Figure 2 provides a surface texture difference between SMA and Conventional Mix Asphalt. SMA is rougher due to its higher proportion of large aggregates compared to the Conventional Mix. This rough texture is a result of the gap-graded aggregate structure of SMA, which features a coarse aggregate skeleton.

In contrast, Conventional Mix Asphalt (CMA) has a denser aggregate gradation with more medium and small-sized aggregates, resulting in a smoother surface. The rough texture of SMA contributes to better rutting resistance and improved load distribution compared to the smoother texture of Conventional Mix Asphalt.

		SMA	DH-S 408	DH-S 408
Name	mm	9.5	9.5	12.5
	inch	3/8	3/8	1/2
Depth	mm	25-35	25-35	40-70
Sieve Size	inch	%Passing by mass	%Passing by mass	%Passing by mass
19	3/4	100	100	100
12.50	1/2	100	100	80-100
9.50	3/8	80-100	90-100	-
4.75	#4	18-60	55-85	44-74
2.36	#8	15-28	32-47	28-58
1.18	#16	13-24	-	-
0.60	#30	-	-	-
0.30	#50	-	7-23	5-21
0.15	#100	9-14	-	-
0.08	#200	7-12	2-10	2-10
% AC by mass		4.0-8.0	4.0-8.0	3.0-7.0

Figure 3 : Gradation of Aggregate for SMA and CMA

(Department of Highways (Thailand))

Figure 3 compares the gradation specifications of two types of asphalt mixtures: Stone Mastic Asphalt (SMA) and DH-S 408 (CMA). At the 9.50 mm (3/8 inch) sieve size, SMA has 80-100% passing, whereas DH-S 408 has 90-100% passing and at the 4.75 mm (#4 sieve) size, SMA shows 18-60% passing compared to 55-85% for DH-S 408. This indicates that SMA is characterized by a more open gradation, allowing for higher coarse aggregate content and fewer fines, which contributes to its durability and resistance to deformation. In contrast, DH-S 408 generally has a higher fine aggregate content, particularly at smaller sieve sizes, making it denser and less open than SMA.

		SMA	DH-S 408	DH-S 408
Name	mm	9.5	9.5	12.5
	inch	3/8	3/8	1/2
Depth	mm	25-35	25-35	25-35
Blows		50	50	75
Stability	(N) Min.	11,565	8,006	8,006
	(lb) Min.	3,000	1,800	1,800
Flows 0.25 mm. (0.01 in)		10-18	8-16	8-16
Percent Air Voids		3-5	3-5	3-5
VMA Min.		15	15	14
Stability/Flow Min. N/0.25 mm.		827	712	712
(lb/0.01 in)		186	160	160
Percent Strength Index Min.		175	75	75
Drain Down		0.3	-	-

Figure 4 : Specification for Marshall Designs for SMA and CMA

(Department of Highways (Thailand))

At present, Thailand does not have a standard for Stone Mastic Asphalt (SMA); it only has a special specification. Figure 4 compares the specifications of SMA and DH-S 408. The table shows that SMA has higher stability (11,565 N minimum compared to 8,006 N), flow (10-18 0.25 mm compared to 8-16 0.25 mm), and strength index (175 minimum compared to 75) compared to DH-S 408.

Additionally, SMA includes a specification for drain down (0.3%) because it may cause drain down due to its higher asphalt content. Moreover, SMA maintains similar air voids (3-5%) and Voids in Mineral Aggregate (VMA) (15%) as DH-S 408, but with a significantly higher stability-to-flow ratio, indicating its superior performance in terms of durability and resistance to deformation. This comparison highlights the potential advantages of adopting SMA for road construction in Thailand.

• SMA mixtures appeared to be more resistant to cracking than dense-graded CMA, probably due to relatively high asphalt contents.

• There was no evidence of raveling on the SMA surfaces.

Experience in Georgia has indicated the following:

• SMA has 30 - 40 percent less rutting than dense graded CMA.

• SMA has 3 to 5 times greater resistance to fatigue cracking compared to dense-graded CMA.

Experience in Germany has indicated that a 20–30 year service life of SMA is not exceptional. Stripping, surface cracking (both temperature and traffic induced), and raveling are failure mechanisms not generally experienced in SMA.(NAPA)

3. Stone Mastic Asphalt (SMA) in Thailand

Stone Mastic Asphalt (SMA) is used by the Expressway Authority of Thailand (EXAT) (Figure4) and the Department of Highways (DOH) (Figure5) in areas with high traffic volumes, such as toll gate areas and motorways. This application leverages SMA's superior durability and resistance to deformation under heavy loads. SMA is used in these critical areas to enhance road performance and lifespan.

Figure 4 : Using SMA at the Din Dang toll gate area by EXAT

Figure 5 : Using SMA at Motorway#9's Ramp by DOH

4. Mix Design

4.1 SMA Job Mix Design

While Thailand currently use slag as the primary SMA aggregate, its limited availability and high costs. In the other hand, Limestone widely abundant and economically viable across the country, emerges as a viable candidate.

4.1.1 SMA Slag Case

In designing the SMA job mix for this research, limestone aggregates with a maximum size of 1/2" will be used along with Polymer Modified Asphalt (PMA) for HMA Ultra-Thin, with an optimum binder content (OBC) of 5.1%. The gradation of the aggregate are as follows.

Bin1 (Filler)	:	Bin2 (Dust)	:	Bin3 (3/8")	:	Bin4 (1/2")
3	:	33	:	10	:	54

4.1.2 SMA Limestone Case

In designing the SMA job mix for this research, limestone aggregates with a maximum size of 1/2" will be used along with Polymer Modified Asphalt (PMA) for HMA Ultra-Thin, with an optimum binder content (OBC) of 5.2%. The gradation of the aggregate are as follows.

Bin1 (Filler)	:	Bin2 (Dust)	:	Bin3 (3/8")	:	Bin4 (1/2")
6	:	18	:	41	:	35

4.2 CMA Job Mix Design

In designing the CMA job mix for this research, referring from Highway 225 Nakhonsawan-Chaiyaphum section1 job mix, a maximum size of 3/4" will be used along with AC40-50, with an optimum binder content (OBC) of 5.2%. The gradation is as follows.

Bin1 (Dust)	:	Bin2 (3/8")	:	Bin3 (1/2")	:	Bin4 (3/4")
48	:	14	:	20	:	18

Table 1 : Job mixes between SMA and CMA

Mix	Aggregate	Asphalt Cement	%AC	Bin (Filler)	Bin (Dust)	Bin (3/8")	Bin (1/2")	Bin (3/4)
SMA	Slag	PMA	5.1	3	33	10	54	0
SMA	Limestone	PMA	5.2	6	18	41	35	0
CMA	Limestone	AC40-50	5.2	0	48	14	20	18

Table 1 compares the job mixes between Conventional Mix Asphalt (CMA) and Stone Mastic Asphalt (SMA), highlighting differences in aggregate compositions and asphalt cement types. The CMA mix uses Limestone as the aggregate and AC40-50 asphalt cement at 5.2% content, while SMA uses both Slag and Limestone aggregates with Polymer Modified Asphalt (PMA) at 5.1% and 5.2%, respectively.

In terms of fillers, the SMA mix with Limestone contains 6% filler, while the SMA with Slag has 3% filler, and the CMA mix has no filler. The dust content also varies significantly, with the Limestone-based SMA containing 18% dust, the Slag-based SMA containing 33%, and the CMA mix having the highest dust content at 48%.

For the 3/8" aggregate size, the Limestone-based SMA has the highest content at 41%, followed by the Slag-based SMA at 10%, and the CMA mix at 14%. The 1/2" aggregate content is 35% for the Limestone-based SMA, 10% for the Slag-based SMA, and 20% for the CMA mix. Notably, the SMA mixes exclude the 3/4" aggregate size, which is included in the CMA mix at 18%.

These variations in aggregate gradation and composition result in distinct performance characteristics between the SMA and CMA mixes, with SMA generally designed for enhanced durability and rut resistance due to its specific aggregate structure.

Table 2 : Marshall Properties between SMA and CMA

		SMA	SMA result	DH-S 408	CMA result
Name	mm	9.5		12.5	
	inch	3/8		1/2	
Stability (lb) Min.		3,000	3,155	1,800	3020
Flows 0.25 mm. (0.01 in)		10-18	14	8-16	13.4
Percent Air Voids		3-5	4	3-5	4.1
VMA Min.		15	15	14	15.1
Stability/Flow (lb/0.01 in)		186	225	160	225
Drain Down		0.3	0	-	

From Table 2, SMA, the stability requirement is a minimum of 3,000 lb, with the SMA result achieving 3,155 lb. In contrast, DH-S 408 has a lower stability requirement of 1,800 lb, with the CMA result achieving 3,020 lb. The flow requirements for SMA are between 10-18 (0.01 in), with the SMA result being 14, while DH-S 408 specifies a flow range of 8-16 (0.01 in) and the CMA result is 13.4. Both SMA and DH-S 408 have a minimum VMA of 15, with SMA meeting this requirement and DH-S 408 specifying 14, with CMA achieving 15.1. The stability-to-flow ratio for SMA is a minimum of 186 lb/0.01 in, with the SMA result being 225 lb/0.01 in. DH-S 408 specifies a stability/flow ratio of 160 lb/0.01 in, with the CMA result also being 225 lb/0.01 in.

5. Indirect Tensile Strength

Indirect Tensile Strength measures a sample's ability to withstand vertically applied force. The ITS test was performed according to (AASHTO T283). To evaluate the ITS, the cylindrical specimen must be placed in the indirect tensile apparatus as shown in figure 6 between the loading strips and be loaded diametrically along the direction of the cylinder axis with a constant speed of displacement until it breaks. The indirect tensile strength is the maximum tensile stress calculated from the peak load applied at break and the dimensions of the specimen. (Veropalumbo et al., 2019)

Figure 6: Indirect Tensile Strength Apparatus

5.1 Indirect Tensile Strength Result

From the results shown in Figure 7, it is evident that Stone Mastic Asphalt (SMA) exhibits a higher Indirect Tensile Strength (ITS) compared to Conventional Mix Asphalt (CMA). Specifically, the SMA mix with Slag as the aggregate achieves the highest ITS value at 0.860 MPa, followed by the SMA mix with Limestone at 0.688 MPa, and the CMA mix at 0.550 MPa. This indicates that SMA, particularly when using Slag, has a significantly greater ability to resist tensile stresses than CMA. The difference between the ITS values of the SMA mixes and CMA mix highlights SMA's superior performance, with the SMA Slag mix demonstrating approximately 25% higher ITS than SMA Limestone and the SMA mix showing about an 22% improvement over the CMA mix by using same aggregate. These findings suggest that SMA may offer enhanced durability and resistance to tensile stress, making it a better option for road surfaces subjected to heavy loads.

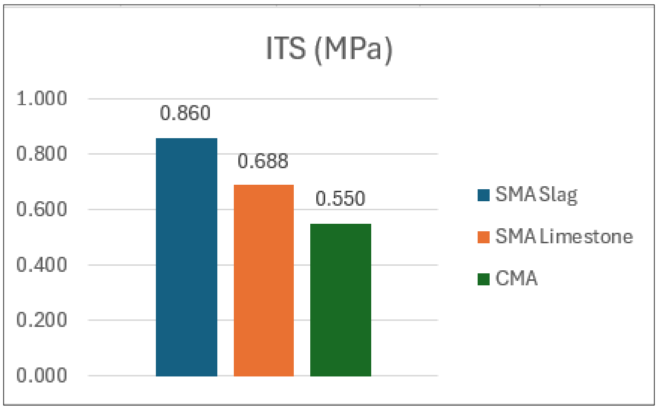

Figure 7: The Indirect Tensile Strength result

6. Resilience Modulus

The Resilient Modulus (MR) obtained from the test indicates the material's resistance to deformation under force, similar to the Elastic Modulus value. Therefore, the Resilient Modulus (MR) value represents the material's strength and is utilized to analyze road structures. It helps calculate movement values and other behaviors of road structures when subjected to force.

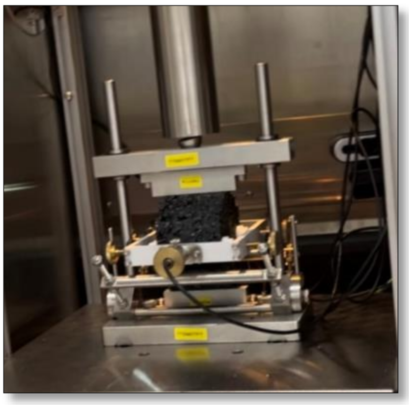

Figure 8: Resilience Modulus Test by Using UTM

6.1Resilience Modulus Result

From the results shown in Figure 9, it is evident that Stone Mastic Asphalt (SMA) exhibits a higher resilience modulus compared to Conventional Mix Asphalt (CMA). The resilience modulus of SMA with Slag as the aggregate is the highest at 1627 MPa, followed by SMA with Limestone at 1517.07 MPa, and CMA at 1357.67 MPa. This indicates that SMA, particularly when using Slag, has a significantly greater ability to resist deformation under load compared to CMA. SMA Slag demonstrates approximately 20% higher resilience compared to SMA Limestone and SMA shows better resilience modulus than CMA about 11% when using same aggregate. These findings underline SMA's superior performance in terms of resistance to deformation, making it a more suitable choice for road surfaces exposed to heavy and repeated traffic loads.

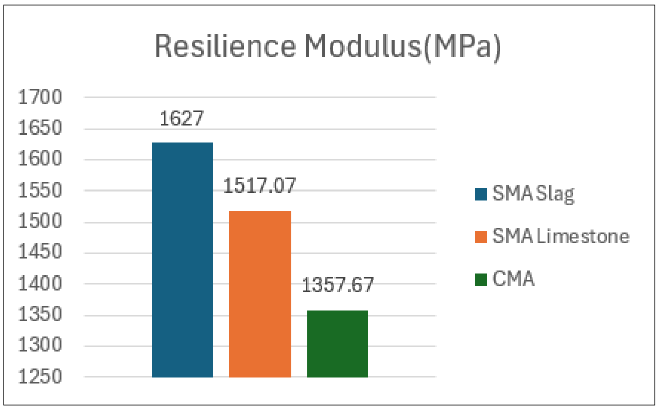

Figure 9: Resilience Modulus Result

7. Hamburg Wheel Tracking Test (HWTT)

The Hamburg Wheel-Tracking Test (HWTT) as shown in Figure12 is performed to measure the rutting resistance of asphalt. In this study, as per (AASHTO T324). The test used specimens with a diameter of 5.9 inches and a height of 2.4 inches. The asphalt mixture specimens were prepared using the Superpave Gyratory Compactor, targeting air voids of 7%±1%, which was verified by measuring the bulk specific gravity of each specimen. During the testing procedure, the specimens were subjected to a metal wheel weighing 158 lb. which passed along the length of the specimens with 50°C. The wheel made 50 passes per minute. The deformation in the specimens was recorded each time the wheel traversed over them. The specimen was considered to have failed if it experienced 12.5 mm of rutting.

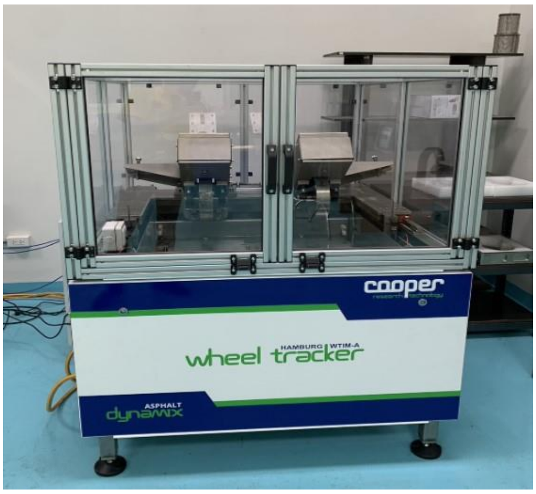

Figure 10: Hamburg Wheel-Tracking
(Department of Highways (Thailand))

From Table 3 and Figure 11, it is evident that Stone Mastic Asphalt (SMA) consistently shows shallower rut depths compared to Conventional Mix Asphalt (CMA), highlighting its superior rutting resistance. At 5,000 passes, the rut depth for SMA with Limestone aggregate is -0.69 mm, and SMA with Slag aggregate is even less at -0.45 mm, while CMA has a significantly deeper rut depth of -1.37 mm. This trend continues as the number of passes increases. At 10,000 passes, the rut depth for SMA Limestone is -0.88 mm and for SMA Slag is -0.74 mm, compared to -1.73 mm for CMA. By 20,000 passes, SMA Limestone records a rut depth of -1.04 mm, and SMA Slag remains shallower at -0.93 mm, whereas CMA reaches -2.21 mm. These results clearly indicate that both SMA mixes, particularly SMA with Slag aggregate, consistently demonstrate superior rutting resistance compared to CMA. The lower rut depths at each stage of the testing process show SMA's enhanced performance under repeated traffic loading, making it a more durable option for high-traffic areas. The Slag aggregate in SMA appears to contribute to even better rutting resistance than Limestone.

Table 3: Final Rut Depth (mm)

Pass No.	5000	10,000	15,000	20,000
SMA Slag	-0.45	-0.74	-0.87	-0.93
SMA Limestone	-0.69	-0.88	-0.96	-1.04
CMA	-1.37	-1.73	-2.03	-2.21

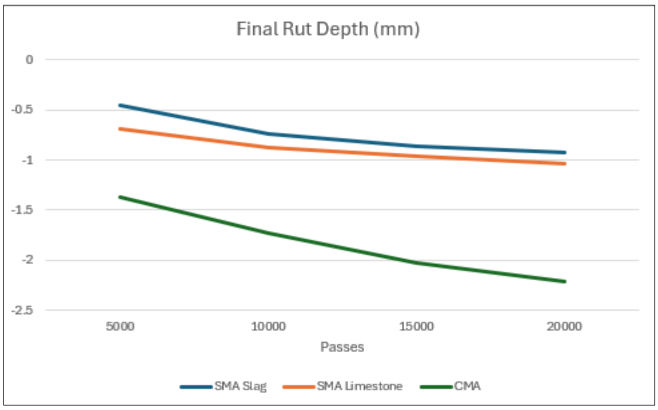

Figure 11: Final Rut depth Result Cost Effectiveness

8. Cost Effectiveness

To consider the cost-effectiveness between using Stone Mastic Asphalt (SMA) and Conventional Mix Asphalt (CMA) for rehabilitation, there is a need to analyze the provided data on rutting resistance performance as shown in Table 3 and Job Mix of CMA and SMA as shown in Table 4.

Estimate the cost per ton for each size of limestone from Chiangrailand Group Co., Ltd., and for asphalt binder from Tipco Asphalt.

Table 4: Cost Estimation of Job Mix (Wearing Course)

Mix	Asphalt Cement Types	Asphalt Cement Price (Baht/ton)	%AC	Filler	Dust 207 Baht/ton	3/8" 278 Baht/ton	1/2" 327 Baht/ton	3/4" 327 Baht/ton	Baht/ton
CMA	AC 40-50	28,000	5.2	0	48	14	20	18	2062.24
SMA	PMA	37,500	5.2	6	18	41	35	0	2658.82

Table 4 shows the cost estimation for CMA and SMA job mixes, with SMA used as a wearing course. For CMA, referring to the Highway 225 Nakhon Sawan-Chaiyaphum Section 1 job mix, a maximum aggregate size of 3/4" will be used along with AC40-50 asphalt cement at 5.2%. The total cost for CMA is 2062.24 Baht/ton. For SMA, a maximum aggregate size of 1/2" will be used along with PMA asphalt cement at the same asphalt content of 5.2%. The cost estimation shows that SMA is more expensive per ton than CMA, primarily due to the higher price of the asphalt cement used in SMA.

Although SMA is more expensive, the increased cost is justified by its superior performance in terms of rutting resistance and durability. As shown in Table 3, the final rut depth of SMA indicates 112.5% better rutting resistance compared to CMA, which suggests that SMA mix is expected to provide a longer-lasting pavement. This could result in lower maintenance and rehabilitation costs over the lifespan of the road. In turn, this could make SMA more cost-effective in the long run, especially in high-traffic or high-temperature conditions.The initial cost per ton of SMA is higher by 596.58 Baht compared to CMA. However, if the long-term benefits of SMA, such as reduced rutting, lower maintenance needs, and increased pavement lifespan, are considered, the investment in SMA could prove to be more economical over time.

9. Conclusion

This research highlights the superiority of Stone Mastic Asphalt (SMA) over Conventional Mix Asphalt (CMA) in several key performance metrics. SMA demonstrated significantly better results in Indirect Tensile Strength (ITS), resilience modulus, and rutting resistance as evaluated by the Hamburg Wheel Tracking Test (HWTT). This indicates that SMA is more durable and resistant to deformation under high-traffic conditions compared to CMA.

Furthermore, within the SMA category, the use of slag as an aggregate outperformed limestone in the same performance tests. SMA with slag showed higher ITS, resilience modulus, and greater rutting resistance, reinforcing its suitability for high-performance pavement applications.

While SMA using limestone with Polymer Modified Asphalt (PMA) is approximately 28.93% more expensive than CMA with AC40-50, the enhanced rutting resistance of SMA about 112.5% better makes it a more cost-effective choice in the long term. The improved performance of SMA justifies the higher initial cost, as it is likely to result in reduced maintenance and longer pavement lifespan, ultimately offering better value for high-traffic and high-temperature roadways.

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Synergizing Pathways for Climate Mitigation and Adaptation in the Road Freight Transport-Energy Sector in Laem Chabang Sub-region, Eastern Thailand

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ABSTRACT

Road freight transport plays a crucial role in distributing goods and services, but its significant contribution to global energy consumption and greenhouse gas emissions drives climate change. Moreover, the sector faces challenges from extreme weather events like heavy rain, floods, and droughts, impacting its infrastructure and services. This study investigates the synergy between climate mitigation and adaptation as pathways in developing sustainable freight transport and energy, focusing on Laem Chabang's sub-region in eastern Thailand. The study mainly uses focus group discussion and quantitative metrics, with frequency analysis. The results highlight the importance of technology and innovation in achieving low emissions, particularly through the adoption of bioenergy fuels, electric light-duty trucks, and pollution capture technologies. Adaptive infrastructure system, such as smart highways with real-time traffic management and advanced energy distribution networks plays a critical role in supporting these pathways. Additionally, regulatory measures and policies, including tax incentives for clean energy use, are essential in driving the transition towards sustainable freight transport and energy systems. These combined efforts demonstrate a comprehensive approach to mitigating emissions and enhancing the resilience of the freight transport-energy sector.

Keywords: Adaptation, Freight transport, Mitigation, Sustainable pathways, Synergy

1. INTRODUCTION

The rapidly growing transport industry, with a 2% annual increase in energy consumption, significantly contributes to global GHG emissions and climate change, particularly in the road freight sector (Aryanpur and Rogan, 2024). Climate change impacts, such as extreme temperatures, intense rainfall, floods, strong winds, and sea level rise, create serious vulnerabilities in energy and transportation infrastructure, systems, and operations (Das, 2020; Ibanez et al., 2016). In Thailand, the demand for road logistics is continuously increasing, with the road freight sector essential for nationwide goods and services transportation (Sattayathamrongthian and Vanpetch, 2023; Chankaew et al., 2018). However, this sector faces significant challenges from extreme climate events, particularly affecting developing industrial hubs (Munpa et al., 2022; Tachaudomdach et al., 2021). Given the susceptibility of transportation and energy sectors to climatic extremes (Yang et al., 2022; Ibanez et al., 2016; Ahmed and Dey, 2020), sustainable development pathways focusing on climate mitigation and adaptation are crucial (IPCC AR6 WGII, 2022; Val et al., 2019).

This study investigates the synergy between climate mitigation and adaptation pathways in developing sustainable freight transport and energy, focusing on Laem Chabang's industrial zone in Chonburi province, Thailand. It explores how these pathways interact in the context of industrial zones, considering infrastructure, technology, innovation, and regulatory measures to enhance sector sustainability and resilience.

2. LITERATURE REVIEW

2.1 Developing pathways to sustainable road transport and energy

Sustainable development aims to meet present needs without compromising future generations' ability to meet theirs (Mensah, 2019; Denton et al., 2015). It integrates social, economic, and environmental concerns into decision-making processes (Purvis et al., 2019; Emas, 2015). This concept is applied in various fields, including economic growth, social progress, climate change, and infrastructure development, focusing on climate actions like mitigation and adaptation (IPCC, 2022). Sustainable development pathways promote the co-evolution of social, technological, and environmental systems, connecting climate change adaptation and disaster risk reduction to enhance resilience (Seidler et al., 2018; Leach et al., 2007). Developing sustainability pathways involves integrating climate actions, balancing human development with environmental health for long-term prosperity (Chan et al., 2020; Lindahl et al., 2016). This includes fostering green technology innovation, reducing GHG emissions, and promoting resource efficiency and resilience to climate impacts (Silva et al., 2024; Nehra et al., 2023). In transport and energy, the focus is on reducing emissions through fuel consumption reduction, deep decarbonization, energy efficiency, and promoting mode shifts (Sun et al., 2023; Dioha et al., 2020). Adaptation pathways address extreme weather with hard measures like improving paving, drainage, and road designs (Pregnolato et al., 2017), and soft measures like planning and maintenance to safeguard infrastructure (Vajjarapu et al., 2019; Wellman, 2015). In Thailand, transport and energy sectors often prioritize hard adaptation measures while lacking in soft adaptations. Efforts are often sector-specific, highlighting the need for integrated pathways connecting transport and energy sectors effectively.

2.2 Synergy between mitigation and adaptation strategies in road freight transport and energy

Understanding the connections between climate change mitigation and adaptation is crucial for creating synergy across different scales and sectors (OECD, 2021). Mitigation typically operates on a broader scale with long-term effects, while adaptation provides immediate local benefits (Wang et al., 2023; Soergel et al., 2021; Locatelli, 2015). In road freight transport and energy, synergy between these strategies is essential for achieving sustainable development goals. Mitigation strategies focus on reducing GHG emissions through improved fuel efficiency, alternative fuels, and advanced vehicle technologies (Nkesah, 2023; Ferrer, 2023; Dagnachew et al., 2021). Adaptation strategies aim to increase resilience to climate impacts like extreme weather and rising temperatures (Melkonyan et al., 2024; Rezvani et al., 2023; Allard, 2021; Rattanachot et al., 2015). Integrating these strategies involves aligning policies to address both emissions reduction and climate resilience (Kwilinski et al., 2024; Tedeschi, 2024; Oliveira et al., 2015). For example, investing in resilient infrastructure supports the efficient operation of low-emission vehicles (Yu et al., 2024; Lopez et al., 2021). Adaptive measures like improved drainage systems enhance transport network reliability, supporting mitigation by maintaining smooth freight movement (Rathnayaka et al., 2023; Iverson and Dervan, 2019). This integrated approach ensures that transport and energy sectors reduce climate change impacts while preparing for its effects, creating a sustainable and resilient system (Nundy et al., 2021; Sharifi and Yamagata, 2016).

3. METHODOLOGY

3.1 Concept and approaches

Road transport-energy consumption and emissions are critical issues requiring improved GHG reduction and enhanced adaptation planning. Developing sustainable pathways for climate mitigation and adaptation is essential (IPCC, 2022). Sustainable Development PathwaySs (SDPs) involve complex climate actions integrating mitigation and adaptation, leading to changes at individual, collective, and systemic levels (IPCC, 2022; Feola, 2015; Hölscher et al., 2018). Utilizing the dynamic adaptive policy pathways methodology (Haasnoot et al., 2019; Haasnoot et al., 2013), the goal is to synergize climate mitigation and adaptation in transport and energy sectors, particularly in urbanizing regions. Focusing on road transport and fuel demand, including infrastructure and services, is crucial. Methods include focus group discussion (FGD) with key stakeholders like local government officials, transport and energy experts, and community representatives to provide qualitative insights into local needs, challenges, and solutions. Quantitative metrics will measure the effectiveness of strategies, assessing reductions in GHG emissions, improvements in energy efficiency, and infrastructure resilience to climate impacts. By combining qualitative insights from focus groups with quantitative data, a comprehensive, context-specific approach can be developed for Laem Chabang in Eastern Thailand.

The study approach involves 3 main steps (refer to Figure 1). First, the study analyzed mitigation and adaptation paths in the road freight transport and energy sectors, using content analysis to identify relevant pathways. Next, the study conducted a focus group discussion with government participants from organizations related to these sectors in the Laem Chabang Sub-region to further refine adaptation and mitigation pathways. Finally, the study looked at how these pathways work together and what benefits they bring using both a mixed-qualitative, thematic analysis and a quantitative, quantitative metrics with frequency analysis method.

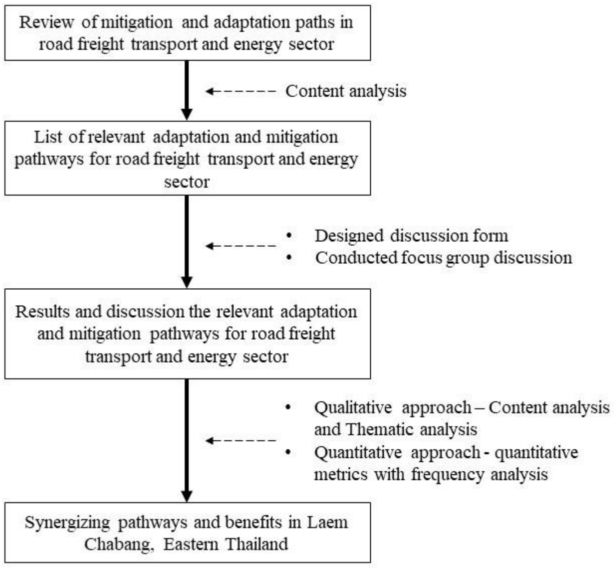


Figure 1 Overall process of the study

3.2 Study area

The Eastern Bangkok Metropolitan Region includes the provinces of Chachoengsao, Chon Buri, and Rayong, with a total area of 13,266 sq.km. and 1,938,408 households. Laem Chabang Sub-region is an important industrial and economic hub located in the eastern part of Thailand. It is part of Chonburi Province and is primarily known for its significant port and industrial activities. The road network is critical for freight transport, facilitating the movement of goods to and from the port and industrial areas. Due to its high level of industrial activity and transport operations, Laem Chabang faces challenges related to greenhouse gas (GHG) emissions and air quality. Efforts to improve energy efficiency and reduce emissions are ongoing. Laem Chabang is also focused on enhancing its resilience to climate change impacts, such as extreme weather events and rising sea levels. This includes both hard infrastructure adaptations and soft policy measures. As the region continues to develop, there is a growing emphasis on sustainability, energy efficiency, and climate resilience to ensure long-term economic and environmental well-being. (Real Estate Information Center 2018; NESDC, 2022; Department of Employment, Ministry of Labor, 2018; 2022).

3.3 Data collection and analysis methods

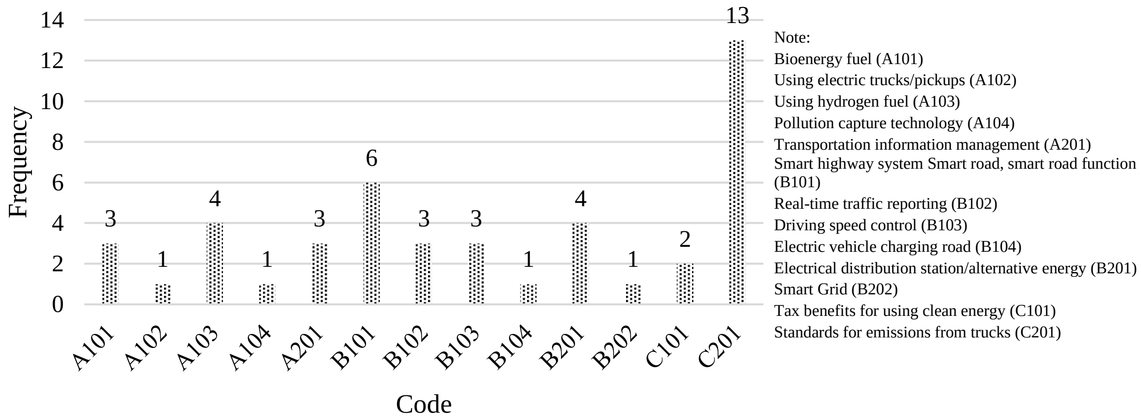
A combination of primary and secondary data sources was used. Primary data involved a FGD held on 27 December 2023 at Laem Chabang Municipality, Chonburi, with 11 participants from relevant government organizations. The aim was to identify sustainable methods for transport energy development, focusing on reducing greenhouse gas emissions and adapting to climate change impacts on transport and energy sectors. Secondary data were sourced from government reports and statistics, including vehicle registrations, fuel consumption, GHG emissions, and infrastructure development from the Department of Land Transport, the Energy Policy and Planning Office, and other relevant Thai government agencies.

The analysis mixed quantitative and qualitative methods. Content analysis was used to review mitigation and adaptation paths related to the road freight transport and energy sectors, and thematic analysis of the FGD identified key themes. These themes were quantified by counting mentions and assigning importance weights, and quantitative metrics with frequency analysis were calculated to prioritize themes to convert qualitative data into quantitative results.

4. RESULTS AND DISCUSSIONS

4.1 Existing mitigation and adaptation paths for freight transport

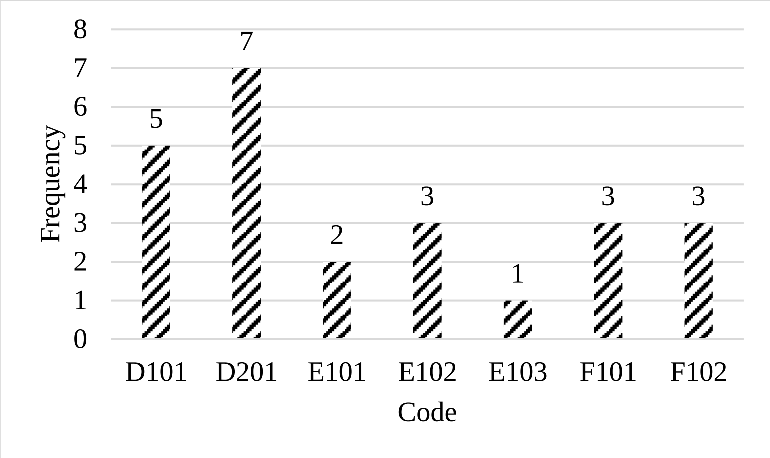
The major mitigation paths typically implement mitigation technology, innovation, infrastructure, policies, and regulations to reduce GHG emissions. The thematic area analysis reveals significant emphasis on various mitigation paths, with emission standards for trucks being the most frequently mentioned topic at 13 occurrences. Other notable topics include smart highway with 6 mentions and both hydrogen fuel use and electric charging stations/alternative energy stations each cited 4 times. Lesser-mentioned but still relevant areas include transportation data management and real-time traffic reporting with 3 mentions each. This quantitative breakdown highlights key focus areas such as emission standards and smart infrastructure, which are crucial for developing sustainable transportation systems (refer to Figure 2).



Source: Based on FGD (2023), and thematic area analysis and frequency analysis

Figure 2 Key focus areas in mitigation paths for freight transport

In addition, the major adaptation paths also implement mitigation technology, innovation, infrastructure, policies, and regulations. Road infrastructure, road networks, climate-resilient construction, and energy infrastructure development are all major adaptation paths. Weatherproof clean energy distribution systems and stations are mentioned at 7 and 5 occurrences, respectively. Other noteworthy topics include the implementation of early warning systems in the transport sector, the promotion of awareness, education, and training, and the establishment of cooperation with government agencies, the private sector, and other organizations. Lesser-mentioned but still relevant areas include pollution capture technologies (refer to Figure 3).



Note:
Developing road infrastructure, road networks and climate-resilient construction (D101)
Energy infrastructure development Weatherproof clean energy distribution system/station (D201)
Real-time traffic weather reporting (E101)
Early warning system in the transport sector (E102)
Air quality detection system (E103)
Creating awareness, education and training (F101)
Creating cooperation with government agencies Private sector and other organizations (F102)

Source: Based on FGD (2023), and thematic area analysis and frequency analysis

Figure 3 Key focus areas in adaptation paths for freight transport

4.2 Synergizing pathways and benefits

In the Laem Chabang sub-region, synergizing climate mitigation and adaptation strategies in the road freight transport-energy sector has resulted in significant benefits (see Table 1). By developing weather-resistant road infrastructure and enhancing flood-resilient designs, the maintenance costs have been reduced, and the road lifespan extended. The establishment of clean energy fueling stations and the adoption of solar rooftops in industrial areas have led to increased clean energy usage and reduced dependency on fossil fuels. Real-time weather and air quality monitoring systems, along with early warning mechanisms, have decreased weather-related delays and improved response times. Additionally, education and training programs have improved compliance and inter-agency collaboration. These synergistic pathways underscore the importance of integrated approaches in enhancing resilience and sustainability within the sector, despite challenges like coordination, regulatory frameworks, and financial constraints.

Table 1 Synergizing Pathways and Benefits for Road Freight Transport

Category	**Pathway**	**Mitigation**	**Adaptation**	**Synergistic Benefits**
Technology	Biofuel and Electric Vehicles	GHG emission reduction	Reduced dependency on fossil fuels	Lower greenhouse gas emissions, improved air quality, enhanced energy security
	Real-time Weather and Traffic Monitoring	Improved logistics and reduced fuel consumption	Enhanced disaster preparedness e.g., heavy rain and floods, reduction in operational drainage delays	Enhanced safety and operational efficiency, better preparedness for weather-related disruptions
Infrastructure	Resilient Roads	Increased road	Decrease in	Reduced

Category	Pathway	Mitigation	Adaptation	Synergistic Benefits
	and Energy Systems	lifespan	power outages in extreme weather	maintenance costs, improved safety, and reliability of infrastructure
	climate-resilient Road and Energy Infrastructure	Decrease in power outages	Increased road lifespan	Enhanced durability and reliability of infrastructure, reduced disruptions and maintenance costs
Smart Systems	Smart Transportation and Real-time Monitoring	Improved fuel efficiency	Reduction in traffic congestion	Optimized logistics, lower operational costs, better traffic management
Education Policy Support	Supportive Policies and Regulations	Tax benefits for clean energy investments	Compliance with new emission and adaptation standards	Accelerated adoption of clean technologies, incentivized investments, improved environmental management
	Educational and Regulatory Measures	Increased awareness and training leading to reduced emissions	Compliance with new adaptation standards	Improved public awareness, better regulatory compliance, enhanced capacity for dealing with climate change impacts

Source: Based on FGD (2023) and thematic area analysis and quantitative metrics analysis

4.3 Discussions

The mixed-methods analysis revealed synergy between climate mitigation and adaptation strategies in the Laem Chabang sub-region's road freight transport-energy sector. Mitigation strategies focus on reducing GHG emissions through improved fuel efficiency, alternative fuels, and advanced vehicle technologies (Nkesah, 2023; Ferrer, 2023; Dagnachew et al., 2021). Adaptation strategies aim to increase the resilience of transport and energy infrastructure to climate impacts like extreme weather and floods (Melkonyan et al., 2024; Rezvani et al., 2023; Allard, 2021; Rattanachot et al., 2015). The implementation of resilient road infrastructure and clean energy in Laem Chabang has shown promising results. Weather-resistant road designs have reduced maintenance costs and increased infrastructure lifespan (Pregnolato et al., 2017). Clean energy fueling stations and real-time weather and air quality monitoring systems, along with early warning mechanisms, have minimized weather-related delays and improved emergency response times.

However, challenges remain, including the need for better inter-agency coordination, robust regulatory frameworks, and increased financial investments. Integrating these strategies involves aligning policies to address both emissions reduction and climate resilience (Kwilinski et al., 2024; Tedeschi, 2024; Oliveira et al., 2015). Investing in resilient infrastructure supports the efficient operation of low-emission vehicles (Yu et al., 2024; Lopez et al., 2021), and adaptive measures like improved drainage systems enhance transport network reliability, supporting mitigation efforts (Rathnayaka et al., 2023; Iverson and Dervan, 2019). This integrated approach ensures that Laem Chabang's transport and energy sectors reduce climate impacts while preparing for them, creating a sustainable and resilient system (Nundy et al., 2021; Sharifi and Yamagata, 2016).

5. Conclusions and Recommendations

The integration of climate mitigation and adaptation paths in the road freight transport-energy sector of Laem Chabang sub-region have demonstrated significant benefits. The combination of resilient infrastructure, clean energy adoption, and advanced monitoring systems has enhanced the sector's sustainability and resilience. These efforts have not only mitigated the impact of climate change but also adapted to its effects, creating a more robust and reliable transport-energy system. Despite the identified challenges, the positive outcomes highlight the potential of synergistic approaches to climate action in this sector.

To advance this synergy, it is recommended to enhance inter-agency coordination and streamline regulatory frameworks, ensuring cohesive and efficient implementation of sustainable practices. This research underscores the importance of integrating mitigation and adaptation paths, advocating for policy alignments that address both emissions reduction and climate resilience simultaneously. Investing in education and training programs is essential to foster a knowledgeable workforce equipped to handle advanced technologies and resilient infrastructure. By focusing on these areas, future research can build on the findings, providing deeper insights into the mechanisms of climate strategy integration. This approach not only enhances the sustainability and resilience of Laem Chabang's freight transport and energy sectors but also serves as a model for other regions facing similar challenges, contributing to the broader academic discourse on climate resilience and sustainable development.

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Addressing socio-economic development challenges through road infrastructure projects

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ABSTRACT

It has become a truism that road infrastructure is an enabler to socio-economic development. Successful implementation of road infrastructure projects is thus of most importance. The impact of road infrastructure projects on socio economic development continues to be the subject of much debate as well as its exact role and influence. By including ex-post analysis as a best practice, the impact of road infrastructure projects on socio economic development can be determined. This is critical as it will help guide economic policy and programmes of a country. The purpose of this research is to determine the impact of road infrastructure projects on socio-economic development, as well as to identify the value of ex-post assessment of road infrastructure projects on socio-economic development. The research adopted a quantitative research approach using a close-ended survey questionnaire as a data source. The target population was 50 participants of which 40 completed the survey, thus having a high response rate of 80%. The collected data was analysed using the online google form survey tool as well as the SPSS statistical tool. It became evident from the results that there is a strong and direct relationship between road infrastructure projects implementation and socio-economic development. Furthermore, that there is value in conducting ex-post assessment of road infrastructure projects on socio-economic development.

Keywords: Road Infrastructure Projects, Ex-post Assessment, Socio-economic Development

1. INTRODUCTION

The relationship between socio economic development and road infrastructure projects is an area of study that is gaining interest globally within the infrastructure community (English, 2015).

The discussion about the relationship between road infrastructure and socio-economic patterns, particularly in developing countries, arises when one considers the exact impact of socio-economic development.

This article outlines the research work conducted where the relationship between road infrastructure project, ex-post assessment and socio-economic development was assessed. Road infrastructure plays a critical role in changing the socio-economic conditions of a country (Sengupta, Coondoo, and Rout, 2016).

The role of roads infrastructure in South Africa (RSA) has been identified as a base in which economic development is built upon.

To measure the impact that roads infrastructure has on socio-economic development that speaks to governments' objectives such as poverty alleviation and job creation as this research study suggests, an ex-post evaluation is critical.

In addressing the research objectives, a set of questions were formulated as shown below:

- What is the impact of road infrastructure projects on socio-economic development?
- What is the value of ex-post assessment of road infrastructure projects on socio-economic development.

2. ROAD INFRASTRUCTURE AND SOCIO-ECONOMIC DEVELOPMENT

RSA invests significant financial resources in road infrastructure intending to curb the social challenges which are predominantly apartheid legacies (Transport, 2017). Makarov, Stepanov, and Kashin (2018) assert that socio-economic development of a country is impacted by large infrastructure projects.

There is growing evidence that suggests lack of research on the impact evaluation of road infrastructure projects ex-post (PIARC, 2019). One of the main purposes of conducting the "Allocation" impact evaluation is to assess the effects of funding ex-post and inform decisions whether scaling up is necessary or not (Muchinsky, 2012).

Ex-post evaluation is a methodology used to evaluate completed projects to verify whether the benefits envisaged during the ex-ante assessment by means of a CBA were realised through the projects (Jong, Vignetti, and Pancotti, 2019).

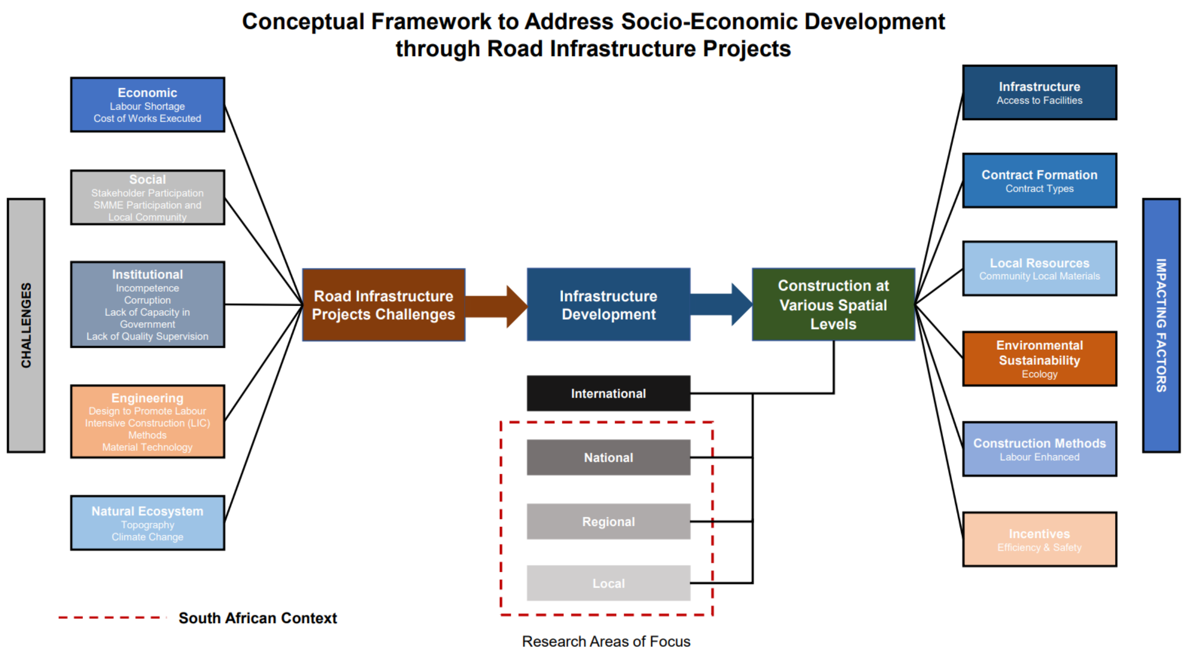
Ex-post evaluation is not popular, yet it is so important in that it enables evaluation of completed projects in order to measure whether the infrastructure does indeed meet the objectives set out ex-ante (Van Damme, Van Geelen, & Courang, 2016). Socio economic development is significantly impacted by roads, but without ex-post analysis, these impacts will not be fully known.

This study illuminates the development research in both the direct and indirect socio-economic impacts of road infrastructure projects as well as the relationship between road infrastructure projects and socio-economic development.

Studies further show that impact of road infrastructure projects ex-post is rarely conducted if at all by transport authorities, which makes it impossible to know if investments have yielded the desired outcome.

Lastly, quantifying social benefits of road infrastructure projects is a topic that is gaining traction. There are various measuring tools being used globally such as Social Impact Analysis tool which evaluates from a wide social perspective, for example job creation.

The following diagram depicts the researchers own conceptual framework of this study:



3. METHODS

The methodology aims to demonstrate the thinking process deployed to collect data in order to draw up the research conclusions. Quantitative research entails a series of methods related to a systematic investigation of social trends, using statistical or numerical data. Quantitative research thus involves measurement with the assumption that it is possible to measure the phenomena under study.

Furthermore, this type of research encompasses analysis of data for trends, relationships and verification of the measurements made (Watson, 2014). Initially, observations were made from researched literature review and identified certain trends (Schachtebeck & Mbuya, 2016).

The research design process for this research work followed the following roadmap:

1) Topic of research;
2) Research problem, questions and hypotheses;
3) Review of current literature;
4) Theoretical framework or methodology;
5) Data collection;
6) Data analysis; and
7) Results.

To address the research objectives a survey questionnaire was adopted as a primary data collection instrument in this study. The targeted population for this research project was 50 (fifty) participants, and the participants were sourced from organisations in the built environment industry particularly the road construction sector.

The researcher sent emails with the survey questionnaire link to the targeted population. This research focused on determining the impact that road infrastructure projects have on socio-economic development, as well as identifying the value of ex-post assessment.

The researcher collected the data using a self-administered Google Forms survey, five-point Likert rating scale questionnaire where influence factors are rated accordingly (Bingham, Asmar & Gibson, 2018). The data collected in this study was through the same data collection process and a consistent set of statements were used for data collection.

The questionnaire responses from the participants were checked and verified through google docs platform which expressed the information in graphs and charts. The information was also captured in an excel spreadsheet in a form of a database. Furthermore, the researcher used SPSS statistical tool to calculate the Cronbach's coefficient alpha (α) to measure the internal consistency of the questionnaire.

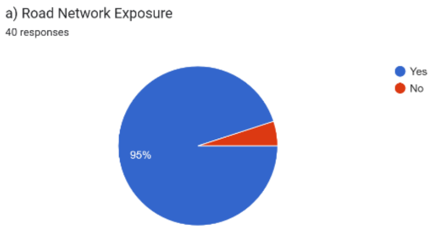
Treiman (2014), defines data analysis as a process where data is broken up into themes namely inspection, cleansing, transformation, and modelling. The main purpose of analysing data is to discover useful information, to identify possible trends or see whether there are any isolated trends, and to further ascertain the theme of the data collected.

Lastly, the instruments used for analysing the data are:

- Google docs for frequency diagram analysis; and
- SPSS statistical tool for descriptive statistics, regression, and correlation analysis.

4. RESULTS

The researcher received 40 responses, which is 80% of the targeted population of 50 individuals. The pictorial view below indicates that the forty (40) participants have road network exposure suggesting that responses on this survey can be relied on, as it was conducted by individuals with the relevant exposure to the road construction industry.



The researcher conducted a Statistics Analysis using SPSS software version 28 to interpret and transform the data into information. The analysis commenced with a reliability test being conducted to establish the degree of consistency between variables.

A Cronbach alpha value of 0.971 was achieved indicating a strong degree of consistency between the variables. This was followed by a Correlation analysis where:

Firstly, Constructs 1 – 4 variables were analysed, and the results depicted that there is a strong and positive correlation of 95.1%, 88.4%, 93.7% and 89.6% between road infrastructure projects challenges, value of ex-post assessment, construction impacting factors and stakeholders' participation, and socio-economic development respectively (see table 1 below):

Correlations

		Road infrastructure projects challenges	Value of Ex-post assessment	Construction Impacting Factors	Stakeholders Participation	Socio-economic develpment
Road infrastructure projects challenges	Pearson Correlation	1	.870**	.980**	.925**	.951**
	Sig. (2-tailed)		<.001	<.001	<.001	<.001
	N	40	40	40	40	40
Value of Ex-post assessment	Pearson Correlation	.870**	1	.826**	.799**	.884**
	Sig. (2-tailed)	<.001		<.001	<.001	<.001
	N	40	40	40	40	40
Construction Impacting Factors	Pearson Correlation	.980**	.826**	1	.927**	.937**
	Sig. (2-tailed)	<.001	<.001		<.001	<.001
	N	40	40	40	40	40
Stakeholders Participation	Pearson Correlation	.925**	.799**	.927**	1	.896**
	Sig. (2-tailed)	<.001	<.001	<.001		<.001
	N	40	40	40	40	40
Socio-economic develpment	Pearson Correlation	.951**	.884**	.937**	.896**	1
	Sig. (2-tailed)	<.001	<.001	<.001	<.001	
	N	40	40	40	40	40

**. Correlation is significant at the 0.01 level (2-tailed).

Table 1: Correlation analysis for constructs 1 – 4 variables

Secondly, the 3 variables were analysed as depicted in Table 2 below. The results indicated that there was a strong and positive correlation of 93.3% and 94.4% between ex-post assessment and road infrastructure project, and socio-economic development.

This means that well implemented road infrastructure projects will contribute positively towards socio-economic development.

Furthermore, consistent value of ex-post assessment of road infrastructure projects equally contributes to socio-economic development.

Correlations

		Ex-post assessment	Road infrastructure project	Socio-economic develpment
Ex-post assessment	Pearson Correlation	1	.905**	.933**
	Sig. (2-tailed)		<.001	<.001
	N	40	40	40
Road infrastructure project	Pearson Correlation	.905**	1	.944**
	Sig. (2-tailed)	<.001		<.001
	N	40	40	40
Socio-economic develpment	Pearson Correlation	.933**	.944**	1
	Sig. (2-tailed)	<.001	<.001	
	N	40	40	40

**. Correlation is significant at the 0.01 level (2-tailed).

Table 2: Correlation analysis of the 3 variables

This was followed by the researcher conducting regression analysis with the results indicating that the R square of 0.925 indicate that 92.5% of the behaviour of socio-economic development depend on the consistent value of ex-post assessment and road infrastructure projects (see table 3 below).

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.962[a]	.925	.921	.294

a. Predictors: (Constant), Road infrastructure project, Ex-post assessment

Table 3: Regression analysis (model summary)

Lastly under Statistics analysis, the analysis of variance (ANOVA) was conducted with the results confirming that the relationship between road infrastructure project, ex-post assessment and socio-economic development is not only strong and positive but is also significant with the P-value less than 1% (see table 4 below).

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	39.577	2	19.789	228.966	<.001[b]
	Residual	3.198	37	.086		
	Total	42.775	39			

a. Dependent Variable: Socio-economic develpment

b. Predictors: (Constant), Road infrastructure project, Ex-post assessment

Table 4: Regression analysis (ANOVA)

The researcher proceeded to analyse the data using Google docs and the results were presented in frequencies (frequency diagrams). Construct 1 (Road infrastructure projects challenges) and Construct 3 (Construction impacting factors) addressed the 1st research objective: To determine the impact of road infrastructure projects on socio-economic development.

One of particular interest under construct 1 was the response to statement number 3 as depicted below:

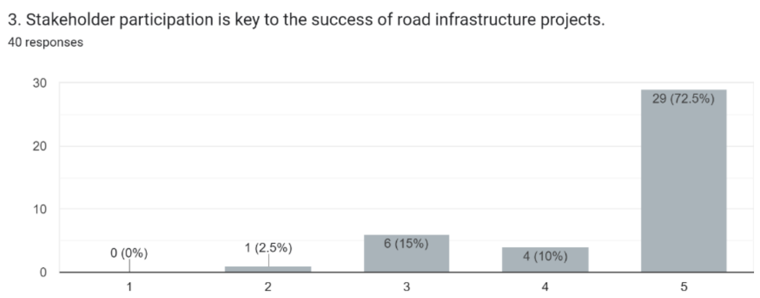


Figure 1: Survey Statement no. 3

Stakeholder participation in a project is a pre-requisite for a successful completion of road infrastructure projects (Matu, Kyalo, Mbugua and Mulwa, 2020).

Respondents who share the same sentiments as Matu et al. (2020) account to a staggering 82.5% (10% agree; 72.5% strongly agree) of responses as reflected in figure 1 above.

Fifteen percent (15%) of the respondents remain indecisive and only 2.5% are of the opinion that stakeholder participation is not key to the success of road infrastructure projects. The findings suggest that majority of the respondents believe that stakeholder participation is critical for the success of roads projects.

Interesting results under construct 3 was the response for statement no. 21 as shown below:

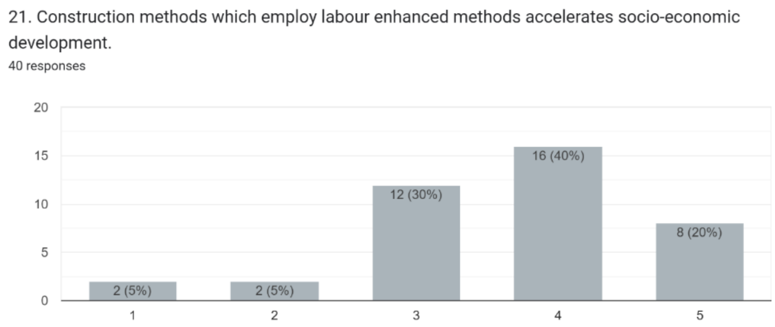


Figure 2: Survey Statement no. 21

Contrary to what the researcher expected, figure 2 above depicts that a large percentage (30%) of the respondents are indecisive when it comes to the impact of employing labour enhanced methods in construction projects. 40% seem to agree and 20% strongly agree with the statement whilst 10% don't (5% strongly disagree; 5% disagree).

The results suggest that a high number of the respondents do not think that construction methods which employ labour enhanced methods accelerate socio-economic development.

Construct 2 (Ex-post assessment) and Construct 4 (Stakeholders participation) addressed the 2nd research objective: To identify the value of ex-post assessment of road infrastructure projects on socio-economic development.

With the focus on the 2nd research objective, under construct 2 the interesting results were from both statements 10 and 14, the results are as follows:

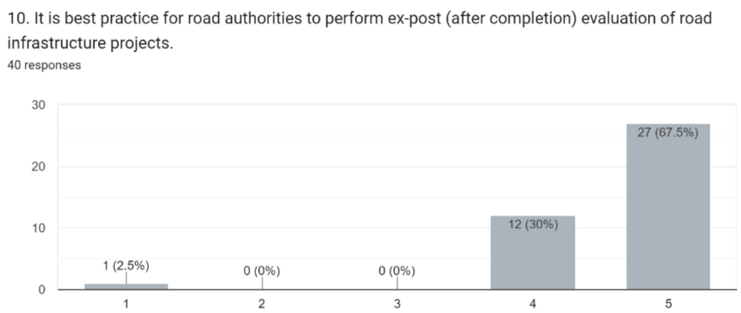


Figure 3: Survey Statement no. 10

In construct 2 the theme is ex-post assessment. An astounding 97.5% (30% agree; 67.5% strongly agree) of the respondents agree that it is best practice for road authorities to perform ex-post evaluation road infrastructure projects.

These results as shown in figure 3 above surprised the researcher because literature reflected that most road authorities only perform evaluations ex-ante. Only 2.5% strongly disagree with this statement.

Lastly, in construct 4 the interesting results were from statement no. 29 and the results are as follows:

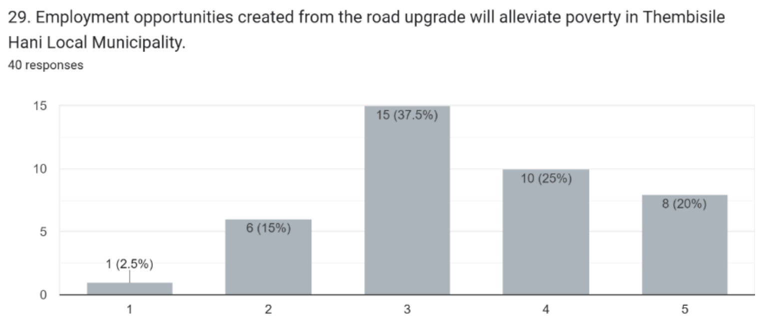


Figure 4: Survey Statement no. 29

Figure 4 above depicts that an overwhelming number of respondents (37.5%) remain neutral when it comes to poverty alleviation as a result of employment opportunities. This result suggests that a sizable percentage of the respondents do not have an opinion on the impact that employment opportunities have on poverty alleviation.

Furthermore, a total of 45% respondents agrees (25% agree; 20% strongly agree) with the statement whilst 17.5% disagreed (2.5% strongly disagree; 15% disagree). It is evident therefore that the respondents are very divided when it comes to the link between employment opportunities and poverty alleviation.

From the results above it is evident that there is definitely a close relationship between the variables. The results confirm that there is a strong direct relationship between infrastructure projects implementation and socio-economic development including the value of ex-post assessment on road infrastructure projects.

5. CONCLUSIONS

This Quantitative research study sought to determine the impact of road infrastructure projects on socio-economic development as well as to identify the value of ex-post assessment of road infrastructure projects on socio-economic development.

And from the findings, the evidence provided a strong, direct relationship between infrastructure projects and socio-economic development.

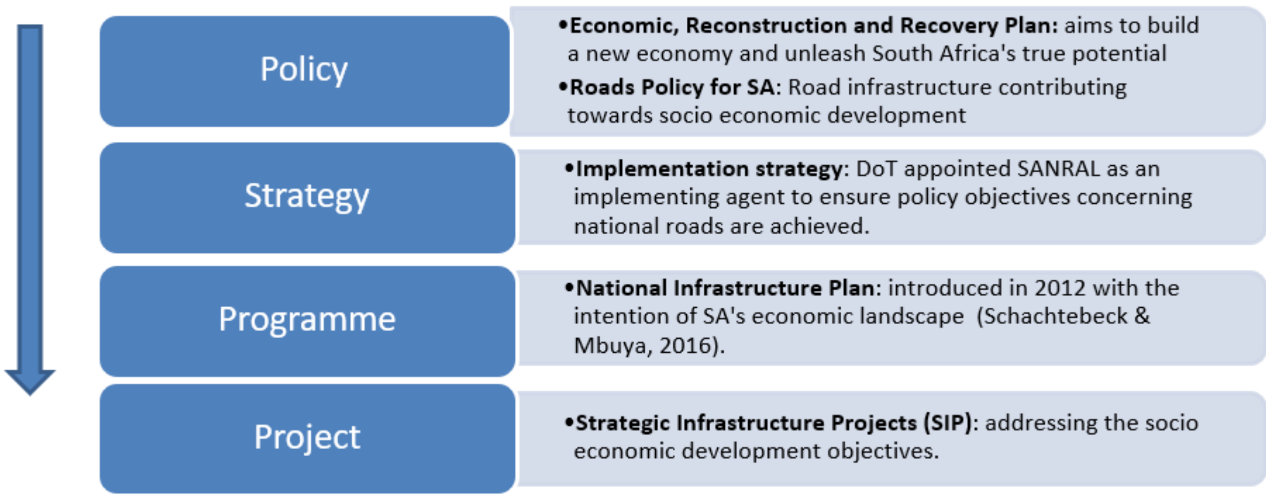
Furthermore, research provided evidence that there is value in conducting ex-post assessment of road infrastructure projects on socio-economic development. The researcher is satisfied that this dissertation met the research objectives.

The results reflected that there is a strong and positive correlation between road infrastructure project and socio-economic development.

This means that a well implemented road infrastructure projects will contribute positively towards socio-economic development.

Lastly, recommendations to policy makers are based on the results from the survey and descriptive statistics, recommendations for the accountable government authorities to:

Develop a socio-economic impact analysis technique that seeks to create a direct link between road infrastructure project objectives and align them to that of national infrastructure policy as depicted in the diagram below:



It is further recommended that ex-post analysis be made mandatory similar to the ex-ante evaluation that is conducted during the feasibility stage.

The researcher suggested that future research could focus on developing an ex-post evaluation methodology with the intention of determining the longer-term effect of policy decisions.

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