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Article

Road network model in Thailand for highly efficient transportation

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Abstract: This research presents a comprehensive model for enhancing the road network in Thailand to achieve high efficiency in transportation. The objective is to develop a systematic approach for categorizing roads that aligns with usage demands and responsible agencies. This alignment facilitates the creation of interconnected routes, which ensure clear responsibility demarcation and foster efficient budget allocation for road maintenance. The findings suggest that a well-structured road network, combined with advanced information and communication technology, can significantly enhance the economic competitiveness of Thailand. This model not only proposes a framework for effective road classification but also outlines strategic initiatives for leveraging technology to achieve transportation efficiency and safety.

Keywords: road network; efficient transportation; intelligent transport systems (ITS); Analytic Hierarchy Process (AHP); fuzzy AHP

1. Introduction

Transportation infrastructure is the backbone of economic growth and development in any nation. In Thailand, the push towards becoming a high-income country has necessitated a significant revamp of its road network systems, particularly in burgeoning economic zones like the Eastern Economic Corridor (EEC) (Sakorn et al., 2017). With increasing globalization and regional integration, the efficiency of transportation networks has emerged as a critical determinant of competitiveness. The Thai government recognizes this and has prioritized enhancing connectivity and mobility through improving its road infrastructure. This research paper sets out to dissect the intricacies of the country's road network, examining its current capabilities and identifying pivotal areas for transformative development. This analysis serves not only to identify the strengths and weaknesses of the existing system but also to establish the critical need for a revamped and forward-thinking road network model. Central to this endeavor is the need to address the persistent challenges faced by road transportation in Thailand.

This research delves into the complexities and methodologies surrounding road network management (Kisgyorgy and Vasvari, 2014; Manjunath, 2013) and classifications, providing the groundwork for current research on Thailand's road infrastructure. It begins by examining the endeavors of the Department of Rural Roads in Thailand, which conducted comprehensive studies to integrate rural roads with the broader highway system. This initiative aimed to consolidate route data and analyze road segregation, considering travel demands, network coherence, and community accessibility to key destinations. Despite producing a preliminary model for provincial, district, and local networks, implementation faced challenges due to legislative decentralization, impeding jurisdiction reassignment over road management. This extensive literature review presents a multidimensional examination of road management (Thongpan, 2016) and classification systems (Chanapai, 2008), incorporating diverse methodologies and case studies to offer an enriched contextual understanding. The aim of this research is to develop an optimized road network model for Thailand that enhances transportation efficiency, particularly in the EEC. This involves establishing a clear classification system for roads based on their usage, traffic volume, and strategic importance, guiding the allocation of maintenance budgets and responsibilities among governing agencies. Additionally, this research aims to investigate the integration of intelligent transport systems (ITS) to improve road safety, manage traffic flow, and reduce congestion, thereby enabling Thailand's transportation infrastructure to support economic competitiveness and equitable regional development. By incorporating these elements, the research aims to address the critical need for a comprehensive, forward-thinking approach to road network management in Thailand, ultimately supporting the country's long-term economic and social objectives. This paper's aim aligns with Thailand's 20-Year Strategic Plan for Infrastructure Development, which underscores the importance of robust infrastructure to propel economic success. This research leverages qualitative insights from industry experts and utilizes the Analytic Hierarchy Process (AHP) to develop a road network model serving as a blueprint for strategic planning and investment, offering a pragmatic roadmap towards a more connected, efficient, and competitive Thailand.

2. Materials and methods

2.1. Sample group

The sample group for this research includes:

- One high-ranking official from the Ministry of Transport, two from the Department of Rural Roads, and two from the Ministry of Interior.
- Eight technical personnel affiliated with the Department of Rural Roads and the Department of Highways in the Eastern Economic Corridor, distributed across various offices: one from Rural Roads Office No. 3, one from Rural Roads Office No. 13, and one each from the rural road districts of Chonburi, Chachoengsao, and Rayong, chosen through purposive sampling.
- Six officials from local government organizations in the Eastern Economic Corridor, including six directors of engineering, with two from Chonburi, three from Chachoengsao, and one from Rayong, also selected through purposive sampling.
- Four hundred road users and freight transporters across the three provinces of Chachoengsao, Chonburi, and Rayong, selected through quota sampling.

2.2. Tools and tool development

Tools used in this research are as follows:

1) Interviews about the condition of the road network for transportation in the Eastern Economic Corridor based on the opinions of personnel from the Department of Highways, Department of Rural Roads, and local government

organizations, responsible for road management in Chachoengsao, Chonburi, and Rayong.

2) Interviews about problems in construction, restoration, and maintenance of roads for transportation, based on the opinions of personnel from the Department of Highways, Department of Rural Roads, and local government organizations, responsible for road management in Chachoengsao, Chonburi, and Rayong.
3) Questionnaires about issues faced by road users and freight transporters in Chachoengsao, Chonburi, and Rayong.
4) Interviews about the criteria for clearly and appropriately classifying roads in Thailand to suit the agencies currently responsible, for the purpose of state budget management, based on the opinions of relevant personnel in Chachoengsao, Chonburi, and Rayong.
5) Interviews about models and methods to improve the road network for efficient transportation, based on the opinions of relevant personnel in Chachoengsao, Chonburi, and Rayong.

2.3. Data analysis method

2.3.1. Analytic Hierarchy Process theory

The Fuzzy Analytic Hierarchy Process (FAHP) is a decision-making tool capable of handling multiple criteria decision making (MCDM) (Kongchuenjai, 2020; Wu et al., 2009), which can encompass both quantitative and qualitative criteria. FAHP is based on the Analytic Hierarchy Process (AHP) developed by Thomas L. Saaty in 1980. FAHP integrates the concept of fuzzy set theory with pairwise comparison, replacing the crisp values used in AHP. This allows FAHP to handle decisions under conditions of vagueness and uncertainty, much like human reasoning, thereby enhancing decision-making efficiency (Chen et al., 2011). FAHP is commonly used to address a variety of problems and is typically found in two main forms: prioritizing criteria and selecting alternatives by comparing multiple criteria across multiple levels.

The Fuzzy Analytic Hierarchy Process is often used for multiple criteria decision making because of its ability to transform qualitative data into quantitative data under uncertain and ambiguous conditions. Hence, it is a technique widely utilized in various applications including studies, research, and business operations which often involve solving various problems and making the most appropriate decisions.

2.3.2. Concepts and fundamental theories

FAHP uses a hierarchical structure to represent the structure of alternatives and evaluation criteria hierarchically (Vaidya and Kumar, 2006). The top level of the structure is called the objective, sometimes also referred to as the goal. The next level down consists of evaluation criteria used to assess the most appropriate alternatives to achieve the best possible outcomes according to the objective. Each evaluation criterion may consist of sub-criteria, which are positioned at the next lower level. Each criterion at the same level should have equal importance, and criteria of lesser importance are placed at a lower level. At the lowest level are the attributes or characteristics of each criterion. An example of the hierarchical structure of FAHP is shown in **Figure 1**.

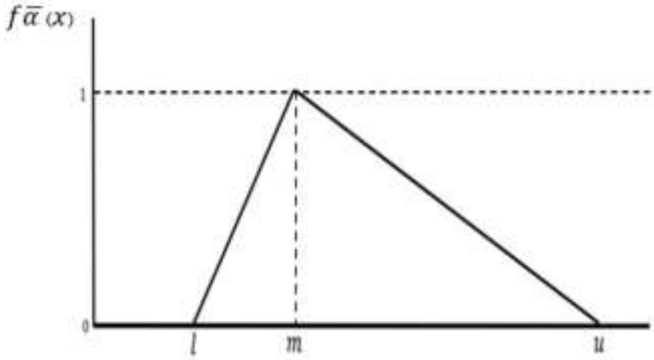

Figure 1. Triangular fuzzy number.

2.3.3. Analyzing the importance weights by comparison

Let $X = \{x1, x2, \ldots, xn\}$ be the set of objects or alternatives (Object Set), and $G = \{g1, g2, \ldots, gn\}$ be the set of goals or decision criteria (Goal Set). Each alternative is analyzed for each decision criterion sequentially. Therefore, the m extent analysis for each alternative can be defined $M_{gi}^{1}, M_{gi}^{2}, M_{gi}^{m}$ for $i = 1, 2, \ldots, n$, where M_{gi}^{j} ($j = 1, 2, \ldots, m$) uses triangular fuzzy numbers for the extent analysis of alternative i for each decision criterion. The calculation steps are as follows:

Calculating the fuzzy synthetic extent values for object i in Equations (1)–(4).

$$s_i = \sum_{j=1}^{m} M_{gi}^{j} \otimes \left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{gi}^{j}\right]^{-1} \tag{1}$$

$$\sum_{j=1}^{m} M_{gi}^{j} = \left[\sum_{j=1}^{n} l_j, \sum_{j=1}^{m} m_j, \sum_{j=1}^{m} u_j\right]^{-1} \tag{2}$$

$$\left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{gi}^{j\ -1}\right] = \left(\frac{1}{\sum_{i=1}^{n} u_i}, \frac{1}{\sum_{i=1}^{n} m_i} \frac{1}{\sum_{i=1}^{n} l_i}\right) \tag{3}$$

$$\sum_{i=1}^{n} \sum_{j=1}^{m} M_{gi}^{j} = \left(\sum_{i=1}^{n} l_i \sum_{i=1}^{n} m_i \sum_{i=1}^{m} u_i\right) \tag{4}$$

Calculating level of possibility of $S_i \geq S_j$ when $S_i = (l_i, m_i, u_i), S_j = (l_j, m_j, u_j); i \neq j$ in Equation (5).

$$(S_i \geq S_j) = \begin{cases} 1 & m_i \geq m_j \\ 0 & l_i \geq u_i \\ \dfrac{(l_i - u_i)}{(m_i - u_i) - (m_i - l_i)} & \text{other} \end{cases} \tag{5}$$

2.3.4. Finding the consistency ratio (CR)

The consistency of the evaluations within both the decision criteria and the alternatives is checked by comparing them against pre-established acceptable values before proceeding with further analysis, as from Equations (6) and (7).

$$\mathrm{CI} = \frac{\lambda_{\max} n}{n - 1} \tag{6}$$

$$\mathrm{CI} = \frac{\mathrm{CI}}{\mathrm{RI}} \tag{7}$$

CR: Consistency ratio, CI: Consistency index, RI: Average random index, which can be estimated from **Table 1** according to the dimension size (n) of the fuzzy comparison matrix, $\lambda_{\max}$: the sum of the ratios divided by the number of decision criteria, n: number of decision criteria.

Table 1. Average random index (RI) (Kabir and Hasin, 2011).

n	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**00**
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.35	1.41	1.45	1.49

The acceptable CR depends on the size of the matrix. For example, for a 3 × 3 matrix, an acceptable CR should not exceed 0.05, for a 4 × 4 matrix, an acceptable CR should not exceed 0.08, and for matrices sized ≥ 5 × 5, the CR should be less than or equal to 0.1 (Kabir and Hasin, 2011). If the CR is higher than the acceptable value, the values set for pairwise comparisons in the fuzzy comparison matrix must be re-analyzed and adjusted (Kwong and Bai, 2002).

This research has gathered data from interviews to study the decision-making criteria for selecting the agencies responsible for road networks. Experts have evaluated the importance of each main criterion pairwise as shown in **Table 2**.

Table 2. Pairwise comparison of main criteria importance.

Main criteria	**Importance of criterion pairwise**				
	A	**B**	**C**	**D**	**E**
A	(1,1,1)	(1,2,3)	(1,2,3)	(5,6,7)	(7,8,9)
B	(1/3,1/2,1)	(1,1,1)	(1,3,5)	(5,6,7)	(3,4,5)
C	(1/3,1/2,1)	(1/5,1/3,1)	(1,1,1)	(3,4,5)	(7,8,9)
D	(1/7,1/6,1/5)	(1/7,1/6,1/5)	(1/5,1/4,1/3)	(1,1,1)	(1,2,3)
E	(1/9,1/8,1/7)	(1/5,1/4,1/3)	(1/9,1/8,1/7)	(1/3,1/2,1)	(1,1,1)

In each level of consideration, the importance assessed by experts is divided into 9 levels of intensity using a fuzzy analytical decision-making process, where A represents the main mission of the agency, B represents physical and utility aspects, C represents management and budget, D represents ITS efficiency improvement, and E represents promotion and efficiency improvement by Smart Highway Control Center. The pairwise importance values of the main criteria are compared based on the triangular fuzzy number principle as shown in **Table 3**.

Table 3. Pairwise comparison of main criteria importance based on triangular fuzzy number.

Criteria	**A**			**B**			**C**			**D**			**E**		
	l	***m***	***u***	***l***	***m***	***u***	***l***	***m***	***u***	***l***	***m***	***u***	***l***	***m***	***u***
A	1	1	1	1	2	3	1	2	3	5	6	7	7	8	9
B	1/3	1/2	1	1	1	1	1	3	5	5	6	7	3	4	5
C	1/3	1/2	1	1/5	1/3	1	1	1	1	3	4	5	7	8	9
D	1/7	1/6	1/5	1/7	1/6	1/5	1/5	1/4	1/3	1	1	1	1	2	3
E	1/9	1/8	1/7	1/5	1/4	1/3	1/9	1/8	1/7	1/3	1/2	1	1	1	1
Total	**1.921**	**2.292**	**3.343**	**2.543**	**3.750**	**5.533**	**3.311**	**6.375**	**9.476**	**14.333**	**17.50**	**21.00**	**23.00**	**23.00**	**27.00**

The results from **Table 3** are used to calculate the consistency of ratings for each criterion in selecting the agency responsible for road networks. The first main criterion example is the main mission of the agency.

$$= \begin{bmatrix} \dfrac{\frac{1}{3.343}+\frac{1}{5.533}+\frac{1}{9.476}+\frac{5}{21.0}+\frac{7}{27.0}}{5}, \\ \dfrac{\frac{1}{2.292}+\frac{2}{3.750}+\frac{2}{6.375}+\frac{6}{17.5}+\frac{8}{23.0}}{5}, \\ \dfrac{\frac{1}{1.921}+\frac{93}{2.543}+\frac{3}{3.311}+\frac{7}{14.333}+\frac{9}{19.0}}{5} \end{bmatrix}$$

$$= (0.217{,}0{,}395{,}0{,}714)$$

Then, a matrix of average values is created, and a membership function is found with *l*, *u* as the lower and upper boundaries respectively, and *m* as the middle value, which represents the ambiguous triangular shape. The weights of the importance of the criteria are then calculated, shown in **Table 4**.

Level $l = \frac{0.217}{0.554} = 0.391$, Level $= \frac{0395}{1.000} = 0.395$, and Level $u = \frac{0.714}{1.933} = 0.369$ respectively.

The defuzzification process is then carried out, changing ambiguous values into numerical values, as shown in **Table 4**.

Table 4. Average values of each main criterion in the form of triangular fuzzy number, the importance scores of each main criterion, and the defuzzification process values.

Main criteria	Score before normalized			Importance scores of each main criterion	Defuzzification process values
	l	***m***	***u***		
A	0.217	0.395	0.714	(0.217,0.395,0.714)	0.387
B	0.147	0.294	0.635	(0.147,0.294,0.635)	0.296
C	0.129	0.208	0.408	(0.129,0.208,0.408)	0.215
D	0.035	0.060	0.102	(0.035,0.060,0.102)	0.059
E	0.027	0.043	0.074	(0.027,0.043,0.074)	0.043
Total	**0.554**	**1.000**	**1.933**		**1.000**

Once the Defuzzification process values for each main criterion are known, the reliability of setting the importance values in the pairwise comparison is checked by calculating the consistency ratio (CR) as follows:

Calculate the consistency index (CI) and find the random consistency index (RI), then calculate the maximum lambda ($\lambda_{\max}$) as shown in the example. Then, the consistency ratio (CR) is calculated.

$$\lambda_{\max} = [0.387]\begin{bmatrix} 1.000,1.000,1.000 \\ 0.333,0.500,1.000 \\ 0.333,0.500,1.000 \\ 0.143,0.167,0.200 \\ 0.111,0.125,0.143 \end{bmatrix} + [0.296]\begin{bmatrix} 1.000,2.000,3.000 \\ 1.000,1.000,1.000 \\ 0.200,0.333,1.000 \\ 0.143,0.167,0.200 \\ 0.200,0.250,0.300 \end{bmatrix}$$

$$+[0.215]\begin{bmatrix} 1.000,2.000,3.000 \\ 1.000,3.000,5.000 \\ 1.000,1.000,1.000 \\ 0.200,0.250,0.333 \\ 0.111,0.125,0.143 \end{bmatrix} + [0.059]\begin{bmatrix} 5.000,6.000,7.000 \\ 5.000,6.000,7.000 \\ 3.000,4.000,5.000 \\ 1.000,1.000,1.000 \\ 0.333,0.500,1.000 \end{bmatrix}$$

$$+[0.043]\begin{bmatrix} 7.000,8.000,9.000 \\ 3.000,4.000,5.000 \\ 7.000,8.000,9.000 \\ 1.000,2.000,3.000 \\ 1.000,1.000,1.000 \end{bmatrix}$$

$$\lambda_{\max} = \begin{bmatrix} \left(\frac{1.494}{0.387} + \frac{1.064}{0.296} + \frac{0.881}{0.215} + \frac{0.243}{0.059} + \frac{0.189}{0.043}\right)/5 \\ \left(\frac{2.106}{0.387} + \frac{1.660}{0.296} + \frac{1.087}{0.215} + \frac{0.313}{0.059} + \frac{0.222}{0.043}\right)/5 \\ \left(\frac{2.719}{0.387} + \frac{2.385}{0.387} + \frac{1.580}{0.215} + \frac{0.396}{0.059} + \frac{0.287}{0.043}\right)/5 \end{bmatrix}$$

$$\lambda_{\max} = (4.011,5.313,7.164) = 5.313$$

$$\mathrm{CI} = \frac{(\lambda_{\max} - n}{n-1} = \frac{5.313-5}{4} = 0.078, \mathrm{CR} = \frac{CI}{RI} = \frac{0.078}{1.12} = 0.070$$

A CR value less than 0.1 indicates that the matrix is consistent with reason and can therefore be accepted.

3. Results and discussion

From the interviews of 21 participants, the results of the fuzzy AHP decision-making process revealed the criteria that influence the selection of agencies to manage road networks and the technology used to enhance road transportation efficiency. High-level managers and related personnel or officials prioritize different criteria from highest to lowest importance using the fuzzy AHP method. The weighted importance from highest to lowest is as follows: (1) the main mission of the agency, (2) physical aspects and utility benefits, (3) promotion and efficiency improvement by Smart Highway Control Centers, (4) supervision and budget management, and (5) efficiency improvement by ITS systems. Interviewees place the highest importance on the agency's main mission, followed by physical aspects and utility benefits, which relate to the expertise of personnel in the agency combined with a budget that can support future road development. Considering survey data from road users who regularly travel within the EEC area, it was found that 97% believe that the Department of Highways should be responsible for main roads, 79% believe that the Department of Rural Roads should handle bypass routes, and 16.2% think that local or local government organizations should be responsible for village roads, minor roads, and focus on community services.

In order to establish criteria for classifying roads in Thailand, defining the study area is crucial so that the developed criteria can be applied to other regions as well. For this purpose, the researcher has chosen the Eastern Economic Corridor Development area, which encompasses all forms of transportation networks that are interconnected in various continuous modes (multi modal). Additionally, this area has clearly defined development plans for the future, which can be used to predict traffic volumes (traffic forecasting) (Wicheansan, 2007) up to the level of service in transportation. This will influence the development of future roadways and necessitate the categorization and designation of primary responsible entities to systematically develop continuous routes, as well as to determine budget allocations for maintenance to ensure the most effective use of the infrastructure. **Table 5** summarizes opinions from the interviews.

Table 5. Summary of opinions from the interviews.

Group	Position/Organization	Results	Discussion	Conclusion
1	High-ranking executive from the Ministry of Transport	**1) Responsibility and jurisdiction adjustments:**	**1) Strategic reallocations and legal flexibility:**	While the roadmap for enhancing Thailand's road infrastructure and management appears well conceptualized, its successful implementation will hinge on overcoming legislative rigidity, refining budgetary frameworks, and embracing technological advancements responsibly. While the existing frameworks for road management in Thailand are deemed adequate there is a clear directive towards enhancing flexibility, clarity, and technology integration to improve road transportation. The push for legal reforms and better budget allocations, suggests a comprehensive approach to future developments in this sector.
		1) Responsibility and Jurisdiction Adjustments: Both executives affirm the current distribution of road responsibilities between national highways, rural roads, and local roads is appropriate but foresee challenges and adjustments due to technological advancements in the next 10–20 years. Operational difficulties arise from non-transferable responsibilities mandated by law, especially for roads spanning multiple jurisdictions or highly-traffic areas requiring specialized maintenance. Despite the suitable current division, there's a notable push for flexibility in transferring responsibilities based on changing urban growth and economic conditions, suggesting adjustments to better accommodate local needs and capabilities.	1) Strategic Reallocations and Legal Flexibility: Enhancing flexibility in operational jurisdiction and budget allocations through legislative adjustments could address many roadblocks. Allowing agencies to adapt dynamically to changing demands without frequent legal revisions could streamline operations. Clear delineation of responsibilities among road authorities is crucial, reducing overlaps and increasing efficiency. Legal reforms for dynamic reassignment of road maintenance responsibilities are needed. Such changes would allow local bodies to scale responsibilities with their capabilities and resources, potentially improving road conditions and administrative efficiency.	
		2) Physical infrastructure and utilization:	**2) Integration of advanced technology (ITS):**	
		2) Physical Infrastructure and Utilization: The categorization into main and feeder roads aligns with international standards, but clearer physical specifications are needed to differentiate road types more distinctly for safer and more efficient use. There's consensus on the appropriateness of existing classifications of main and secondary roads, but concerns about overlaps and the need for clearer distinctions between responsibilities to prevent jurisdictional confusion and inefficiencies. Both executives agree that the current distribution of road responsibilities is generally suitable but indicate the need for flexibility in transferring responsibilities between local and national agencies based on evolving urban dynamics and capabilities.	2) Integration of Advanced Technology (ITS): The idea of equipping each province with a traffic control center using real-time data and surveillance technology could significantly impact public safety and traffic efficiency. Investing in ITS could enhance road management, reduce accidents, and improve traffic flow. However, these systems must be robust enough to justify their 'smart' designation. Regular updates and evaluations are essential. Additionally, adopting explicit standards for road design that consider speed, safety, and the specific roles of various road types could improve traffic management and safety outcomes.	

Table 5. (*Continued*).

Group	Position/Organization	Results	Discussion	Conclusion
1	High-ranking executive from the Ministry of Transport	**3) Budget allocation and management:**	**3) Strategic budget management:**	Although Thailand's highway system is robust, there are several areas where improvements can be made, particularly in flexibility of management, budget allocations, and technology integration. These changes could lead to more responsive and efficient road management practices better suited to modern transportation networks' dynamic needs. While the current road jurisdiction and management system in Thailand is deemed effective, ongoing adjustments will be necessary to address future challenges brought by technological advancements and changing urban landscapes. Effective budget management, strategic integration of technology, and flexible legal frameworks will be key to maintaining and enhancing the road transport system's efficiency and safety.
		Budget allocations are deemed insufficient for the maintenance needs dictated by the responsibilities of main road agencies. Local bodies tasked with diverse responsibilities face budgetary strains affecting road maintenance and development. Budget constraints are identified as a major longstanding issue. While the Department of Rural Roads receives adequate maintenance funds, the executives recognize that much of the national budget is consumed by personnel costs, limiting funds available for development. The local entities are seen as underfunded, especially when considering their broad responsibilities beyond road maintenance.	Effective budget management is crucial. The emphasis on reallocating resources towards road maintenance and development, rather than overwhelmingly towards personnel, suggests a need for a more strategic approach. Reevaluating the funding model to ensure that local bodies receive adequate financial support is critical. This would empower local administrations to maintain and improve infrastructure without compromising other civic responsibilities. A more equitable and strategic redistribution of funds is necessary.	
		4) Technological enhancement (ITS):	**4) Public-private partnership:**	
		Both executives recognize the value of adopting Intelligent Transportation Systems (ITS) to enhance road efficiency and safety. They advocate for more substantial investments in technology to reduce operational costs and improve service delivery, although they acknowledge the high initial costs and public skepticism regarding the value of such technologies. There is strong advocacy for the adoption of ITS to enhance road efficiency and safety. The executives discuss the potential of ITS in improving communication between roads and drivers, contributing to safer and more efficient travel.	A proposal to encourage public-private partnerships, particularly in technology deployment and road maintenance, could alleviate financial pressure on the government while accelerating infrastructure improvements. There is an implication that both public and private sectors should play vital roles in developing and implementing transportation technologies. Public-private partnerships might be encouraged to offset costs and leverage private-sector innovation and efficiency.	
		5) Development and efficiency of transportation:	**5) Long-term planning and implementation:**	
		The implementation of Intelligent Transportation Systems (ITS) is agreed upon as beneficial. However, there's concern that expectations for "Smart Highways" may lead to discrepancies between names and actual capabilities. The promotion of ITS and Smart Highway technologies is agreed upon as necessary, but significant investment for installation and maintenance requires a cautious approach. There is a strong endorsement for the integration of technology to manage road use and safety effectively. Suggestions include creating centralized traffic control centers in each province to manage traffic in real time and reduce accidents and crime rates.	Implementing a phased approach to ITS and Smart Highway projects, starting with economically significant cities, could provide a template for nationwide expansion. This would allow for adjustments and refinements based on initial outcomes. The road management system must remain flexible to accommodate rapid technological changes. It is essential to consider how these projects will evolve, ensuring that long-term goals align with technological advancements and urban development trends. This could include reassessing which roads are classified as rural or local.	

Table 5. (*Continued*).

Group	Position/Organization	Results	Discussion	Conclusion
2	30 Engineering personnel from the Department of Rural Roads in the Eastern Economic Corridor	**1) Division of road responsibility:**	**1) Clarification of responsibilities:**	By addressing these points, road management in Thailand's Eastern Economic Corridor can be optimized to better serve the economic activities and ensure safer, more efficient transport infrastructure.
		The current division of road responsibilities among three major units (national highways, rural roads, and local roads) is well-recognized by road users. However, the distinction between these road types is still not clear due to uniform construction standards (Yimsiri and Ratanaikom, 2020) and safety equipment used across different types of roads.	There is a need for clearer guidelines and standards that distinctly define the responsibilities for different types of roads. This would help in reducing confusion among road users and streamline maintenance and emergency responses.	
		2) Legislative restrictions:	**2) Legislative flexibility:**	
		Most personnel are not in favor of existing legal restrictions that prevent the transfer of road responsibility to other agencies. They argue that such restrictions impede flexibility and adaptability in road management, especially when local agencies like Provincial Administrative Organizations (PAOs) lack sufficient budgets for road maintenance.	Amending laws to allow more dynamic assignment of road responsibilities could help respond more effectively to the changing needs of road infrastructure. This is particularly crucial in areas experiencing rapid growth, where the existing road managing body may not be equipped financially or technically to handle the increased traffic and maintenance demands.	
		3) Budget allocation and management:	**3) Budgeting and funding:**	
		There is a call for more flexibility in budget allocation to enable timely upgrades and maintenance, which is currently hindered by stringent legal frameworks.	More flexible budgeting that allows for reallocation of funds based on current road conditions and traffic demands could enhance the overall efficiency of road maintenance. Moreover, exploring alternative funding sources, such as public-private partnerships, could provide additional financial support without overburdening any single agency.	
		4) Adapting to changes:	**4) Technology integration:**	
		There is strong support for legislative amendments that would allow road management responsibilities to be adjusted based on changing economic and urban conditions, especially in rapidly developing areas like the Eastern Economic Corridor.	Integrating modern technologies like ITS can significantly improve road safety and traffic management. However, ensuring that such technologies are cost-effective and backed by a solid maintenance framework is essential. The government could facilitate this by standardizing costs and specifications to reduce the financial risk associated with technological investments.	
		5) Use of technology (ITS and Smart Highways):	**5) Training and workforce development:**	
		The personnel are in favor of adopting Intelligent Transportation Systems (ITS) and Smart Highways to enhance road efficiency and safety. However, they expressed concerns about the high costs associated with the implementation of such technologies, especially when relying on imported materials and equipment.	As technological solutions like Smart Highways are adopted, there is a pressing need for specialized training for existing personnel and hiring of tech-savvy staff. This could involve partnerships with educational institutions to ensure a steady pipeline of qualified professionals capable of managing advanced transportation systems.	

Table 5. (*Continued*).

Group	Position/Organization	Results	Discussion	Conclusion
3	130 Local administrative organizations	**1) Responsibility and standards:**	**1) Standardization of practices:**	While the existing management framework for roads in the Eastern Economic Corridor is functional, there is a clear need for reforms to enhance flexibility, improve standards, and integrate modern technologies. Such changes could significantly boost the efficiency and safety of the road network, supporting the region's ongoing economic growth.
		Participants generally agreed that the current division of road responsibilities among different administrative levels is suitable for the present conditions. However, discrepancies arise due to variations in geographical mapping and actual terrain, leading to the use of non-uniform standards that complicate maintenance and development tasks.	Developing uniform standards for road construction and maintenance that accommodate the specific geographical and economic conditions of different LAOs could help alleviate some of the current challenges. This would also ensure consistency in road quality across different jurisdictions.	
		2) Legislative constraints:	**2) Legislative reforms:**	
		There is a significant consensus against the legislative restrictions that prevent the transfer of road responsibilities. Most personnel advocate for law amendments to provide more flexibility in budget allocation and operational control, which they believe would lead to more balanced and efficient management.	Modifying existing laws to allow for more dynamic management of road responsibilities could lead to better resource allocation and more responsive infrastructure management. This is particularly crucial for adapting to the economic developments within the corridor.	
		3) Role adjustment:	**3) Enhanced coordination:**	
		There is strong support for the idea that LAOs should have the ability to elevate or shift the oversight of certain roads based on specific needs and economic changes, particularly in rapidly developing areas like the Eastern Economic Corridor.	Improved coordination between LAOs and major road agencies could foster better planning and execution of road works. Establishing clear guidelines for when and how responsibilities can be transferred or shared may help reduce redundancies and inefficiencies.	
		4) Physical and utilitarian aspects:	**4) Technology integration**:	
		The classification of roads into major, collector, and local roads is well understood and agreed upon. It is recognized that this classification aligns well with physical realities and administrative duties, ensuring that road maintenance and improvements are adequately managed.	While there is support for adopting advanced technologies like Intelligent Transportation Systems (ITS) and Smart Highways, concerns about cost effectiveness and implementation challenges remain. It is suggested that investments in technology should be carefully evaluated against potential benefits, particularly in terms of cost savings and improvements in safety.	
		5) Budget allocation:	**5) Funding strategies:**	
		The allocation of funds is deemed sufficient for primary agencies like the Department of Highways and the Department of Rural Roads. However, local entities face significant challenges due to inadequate budgets, which hampers their ability to maintain and upgrade roads effectively.	Exploring alternative funding strategies, such as public-private partnerships or dedicated road funds, could provide LAOs with additional resources necessary for maintaining and upgrading their road networks.	

From this interview data, using weighted consideration criteria through the fuzzy AHP process, a table categorizing road types (Chanapai, 2008; Öberg et al., 2018) by agency responsibility can be summarized as **Table 6**.

Table 6. Categorizing road types and consideration criteria by agency responsibility.

No.	Road types	Consideration criteria	Responsible agency
1	Arterial roads	Serve as connectors between regions, provinces, and districts, emphasizing mobility. • physical components include a traffic surface width of more than 7.00 m, • road shoulders ranging from 1.50–2.50 m, • accommodating traffic volumes of 1000–8000 vehicles/day, • speed limits of 90–110 km/h.	Department of Highways
2	Collector roads	Act as feeders, channeling traffic from main roads into communities and connecting main and secondary roads. • physical components include a traffic surface width of 6.00–7.00 m, • road shoulders ranging from 0–1.50 m, • accommodating traffic volumes of 300–1000 vehicles/day, • speed limits of 60–90 km/h.	Department of Rural Roads
3	Local roads	Distribute traffic from secondary roads to access areas comprehensively, emphasizing accessibility. • physical components include a traffic surface width of less than 6.00 m, • road shoulders ranging from 0–1.00 m, • no specific traffic volume set, • a maximum speed limit of 60 km/h.	Local Government Organizations
4	Strategy roads	Serve as strategic support roads for area development, connecting travel to tourist destinations, industrial zones, transportation stations, ports, airports, factories, and warehouses, as well as for border trade and royal initiative projects.	Department of Highways/Department of Rural Roads

From the decision-making process using the fuzzy AHP method, it is evident that the criteria influencing the decision to select agencies for overseeing road networks and enhancing road transportation efficiency are weighed differently by the interviewees. The top two priorities are: (1) the main mission of the agency, weighted at 0.39, which includes the primary construction and maintenance responsibilities held by the Department of Highways and the Department of Rural Roads, and (2) physical aspects and utility benefits, weighted at 0.19, The interviewees emphasize that the Department of Highways should be responsible for main routes, the Department of Rural Roads for secondary routes and bypasses, and local or local government organizations for local roads within communities. The highest priority is given to the main mission of the agencies, followed by physical aspects and utility benefits, due to the expertise of the personnel involved and the budget available to support future road development. This aligns with survey data from road users in the EEC area, showing that 49.75% believe the Department of Highways should manage main roads, 64.00% support the Department of Rural Roads for secondary and bypass routes, and 83.00% think local government organizations should handle local and community roads. These priorities reflect that major agency like the Department of Highways and the Department of Rural Roads, with their specialized personnel and adequate budgeting, are better equipped to maintain significant physical roads, such as those leading to industrial areas, tourist spots, and airports. If local government organizations receive increased funding, they could also efficiently maintain their roads to a standard comparable to that of the major agencies. The main issues with roads under local governance, transferred from major agencies as per the Decentralization Act of 1999, include:

- The non-continuous transfer of roads, hindering consistent maintenance.
- The lengthy transfer process, during which the conditions of roads have changed; for example, what were once secondary networks have become main roads requiring more significant maintenance, beyond the fiscal capabilities of local organizations.
- The legal framework which prevents the re-transfer of roads back to major agencies.
- The lack of specialized personnel transferred to local bodies under the decentralization plan, leading to a shortage of expertise in road management.

To address and mitigate these issues, and to enhance the efficiency of road transportation in Thailand sustainably, three main components should be considered:

Legal amend decentralization laws to allow for more flexible re-transfer of roads to major agencies, especially when roads have gained importance and traffic density.

Personnel enhance the capabilities of local agency staff in road management.

Budget Increase funding or allow local agencies to request additional budgets from external or central government agencies on a case-by-case basis, or consider transferring certain local roads to the Department of Rural Roads, which has adequate funding for maintenance.

As the considerations highlighted in the decision-making process, a proposed model for a highly efficient road network that addresses the specific needs and strategic goals of Thailand, particularly within regions like the Eastern Economic Corridor (EEC) are summarized as follows:

Road network model for highly efficient transportation:

Key issues of applying a road network model for Thailand should consider that its road network not only meets current transportation needs but is also resilient and adaptable to future demands and innovations. This approach will help in promoting sustainable development, enhancing economic growth, and improving overall road safety and mobility in the region. A proposed model for a highly efficient road network (**Figure 2**) is described as follows:

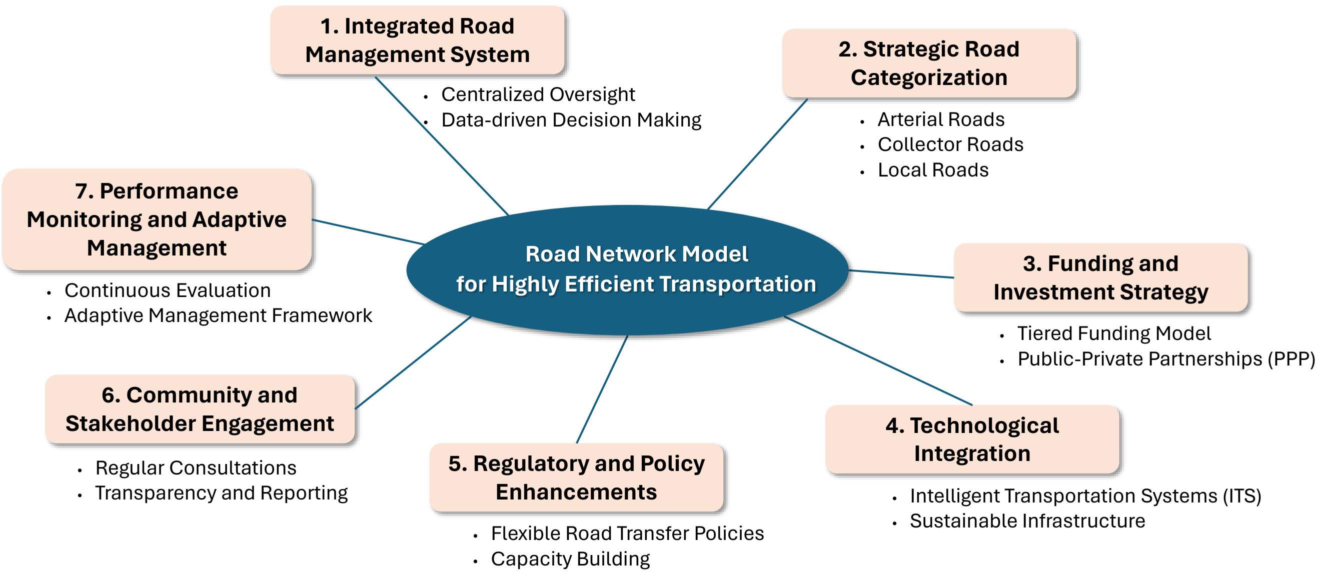

Figure 2. Proposed road network model for highly efficient transportation.

1) Integrated road management system
    - Centralized oversight establishes a central road management authority that oversees all major road projects and maintenance schedules across different agencies. This would ensure uniform standards and coordination.
    - Data-driven decision making implement a comprehensive data collection and analysis framework that includes traffic monitoring, road condition assessments, and user feedback to inform road maintenance and development.
2) Strategic road categorization
    - Arterial roads managed by the Department of Highways, these roads would serve as the backbone of the national transport network, connecting major cities, economic zones, and regions.
    - Collector roads managed by the Department of Rural Roads, these would facilitate the movement from arterial roads to local and community areas, supporting economic activities like tourism and local trade.
    - Local roads managed by local government organizations, focusing on accessibility within communities and linking with collector roads.
3) Funding and investment strategy
    - Tiered funding model allocate budgets based on the strategic importance and usage of roads. Higher funding for arterial roads and economically significant routes.
    - Public-private partnerships (PPP) encourage private investment in road development and maintenance, especially for arterial and collector roads that can generate economic returns.
4) Technological integration
    - Intelligent Transportation Systems (ITS) deploy ITS across all road categories to enhance traffic management, safety, and efficiency. This includes real-time traffic data, automated traffic control systems, and advanced safety features.

- Sustainable infrastructure incorporates green technology in road construction and maintenance to reduce environmental impact, such as using eco-friendly materials and solar-powered road signs.

5) Regulatory and policy enhancements
   - Flexible road transfer policies reform policies to allow dynamic reassignment of road management responsibilities as traffic patterns and regional development needs evolve.
   - Capacity building invest in training and development programs for local government personnel to enhance their expertise in road management and ITS technologies.
6) Community and stakeholder engagement
   - Regular consultations engage with local communities, businesses, and other stakeholders in the planning and decision-making process to ensure that the road network meets their needs.
   - Transparency and reporting implement transparent reporting and accountability mechanisms to build public trust and ensure efficient use of funds.
7) Performance monitoring and adaptive management
   - Continuous evaluation establishes benchmarks for road efficiency and safety, regularly assessing road network performance against these standards.
   - Adaptive management framework be responsive to new challenges and opportunities by adapting strategies based on performance data and technological advancements.

4. Discussion

The proposed model for a highly efficient road network introduces several advancements and improvements over traditional or existing road network systems (Hu and Wu, 2012) by enhancing the current practices as follows:

1) Centralized oversight and coordination
   - Old approach road management might be fragmented among different agencies (Injan et al., 2009) with little coordination, leading to inconsistent standards and redundant efforts.
   - New model centralized oversight ensures uniformity in road standards and project execution across all regions and agencies, leading to more coherent and efficient road management.
2) Data-driven decision making
   - Old approach decisions might be based more on historical practices and less on real-time data, potentially overlooking evolving traffic patterns and needs.
   - New model integrates advanced data analytics to make informed decisions based on current and projected traffic data, road usage, and user feedback, ensuring that the infrastructure developments are responsive to actual needs.
3) Funding and investment strategy
   - Old approach funding may be allocated uniformly or based on outdated

criteria, which may not accurately reflect the current needs or economic potential of road projects.
- New model implements a tiered funding model that prioritizes roads based on strategic importance and potential for economic return, coupled with encouraging private investment through PPPs.

4) Technological integration
   - Old approach limited use of advanced technologies in traffic management and road safety, with sporadic updates and upgrades.
   - New model comprehensive deployment of Intelligent Transportation Systems (ITS) (Al Mahairzi and Reddy, 2017; Ozaki, 2018) across all road types to optimize traffic flow, enhance safety, and support sustainable practices like green technologies.
5) Regulatory and policy enhancements
   - Old approach static policies that may not adapt well to changing urban and economic landscapes, with rigid road management responsibilities.
   - New model flexible road transfer policies and dynamic legislative frameworks that allow for the adjustment of responsibilities as road significance and regional needs evolve.
6) Community and stakeholder engagement
   - Old approach often minimal direct engagement with local communities and stakeholders in the planning process, leading to solutions that might not align with local needs.
   - New model regular, structured engagement with communities and stakeholders ensures that the road network serves actual local and regional needs (Qian et al., 2012) and builds public trust through transparency.
7) Performance monitoring and adaptive management
   - Old approach periodic or infrequent evaluation of road network performance, with limited responsiveness to identified issues.
   - New model continuous performance monitoring with established benchmarks and an adaptive management framework that swiftly incorporates feedback and technological advancements into road network planning and maintenance.

These improvements are able to create a more resilient, responsive, and sustainable road network system that aligns with modern traffic demands, economic needs, and technological possibilities, setting a foundation for future developments in infrastructure within Thailand and potentially other regions.

5. Conclusion

Considering these criteria for responsibility and budget allocation, the agencies can be more clearly identified, allowing them to expedite the development of road networks to support economic growth, improve roadwork, and enhance safety without conflicting with existing decentralization laws. This would ensure a complete road network in the area, with interconnected routes managed without restriction by the responsible agency. In terms of Intelligent Transportation Systems (ITS), it can be concluded that ITS is beneficial according to modern management and budgeting principles, using information and communication technology to help manage traffic and transportation, enhancing road transport efficiency, safety, and reducing traffic congestion. The basic objectives and principles of ITS include: 1) driver assistance, 2) driver acceptance, and 3) social acceptance.

As Thailand has not yet developed ITS to match international standards, strategies should be devised to promote the development and implementation of ITS to support road transportation more extensively, based on the necessity to:

- Enhance the transport and logistics capacity.
- Promote continuous and diverse multi-modal transportation.
- Support transportation and traffic management.
- Be prepared for emergencies and incidents.
- Boost tourism to stimulate the economy.

These strategies should encompass management under a single command center, which could reduce personnel workload and automatically gather data, helping to share useful information about traffic volumes, types of vehicles, speeds, accident patterns, load control, and other security and safety operations, utilizing Big Data effectively within the transportation system.

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