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Evaluation of the Transport Environmental Effects of an Urban Road Network in a Medium-Sized City in a Developing Country

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Abstract: A decision support model (DSM) involving a combination of five different prediction models for the environmental effects of transport and the powerful HMADM approach was introduced for the first time to assess the multiple criteria environmental effects of transport in an urban road network of the Khon Kaen Metropolitan Municipality (KKMM) in Khon Kaen City, Thailand. Five mathematical models were adopted to quantify the CO_2 emissions (CO2Es), $PM_{2.5}$ concentration (PM2.5C), CO concentrations (COCs), noise levels (NOLs), and pedestrian accident risk (PAR) values of all road segments in the study area. The FAHP, FSM, and TOPSIS were integrated into the HMADM to estimate the composite transport environmental effect scores (CTEESs) of each road segment. The FAHP was applied to determine the relative weights of each environmental criterion for three land use types, and the FSM was utilized to transform linguistic (fuzzy) scores into numerical (crisp) scores. Both the FAHP and FSM are principally used to deal with uncertain, incomplete, and ambiguous (fuzzy) information that appears during decision-making processes. Finally, TOPSIS was used to estimate the CTEESs of each road segment. An integrated DSM was applied to comprehend and evaluate each individual environmental criterion and the combined environmental criteria for each road segment in the study area. The DSM was employed to rank the problematic locations of all road segments. For instance, the ranking of the top 12 road segments with the greatest CTEESs was 75, 80, 48, 89, 76, 5, 64, 59, 60, 16, 65, and 62. In addition, this DSM can also be used to identify the possible causes of such locations and allocate limited government budgets for the implementation of appropriate remedial measures for resolving such environmental problems due to transport in an urban road network in the study area.

Keywords: sustainability; environmental impacts evaluation; MMM; HMADM; FAHP; FSM; TOPSIS; DSM

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1. Introduction

As both developing and developed countries continue to urbanize, rapid urban growth is anticipated, particularly in low- and middle-income countries [1]. This will inevitably lead to enhancements in economic development, as well as the expansion of production, population, employment, travel demand, and freight transport demand in urban road networks. Transport can potentially lead to multiple social and environmental effects, such as difficulty with access, social severance, pedestrian accident risk, higher noise levels, greater air pollution, global warming, climate change, and other adverse consequences [2]. These effects strongly influence the health and well-being of the residents of urban areas [3]. To address these problems, a sustainable urban land use and transport planning (SULT) process is essential for ensuring sustainable and livable cities and societies [4].

Recently, the UNDP announced 17 sustainable development goals (SDGs) in association with 169 targets to promote a balance among the economic, social, and environmental elements of sustainable development and encourage the execution of important actions in the future [5]. Some examples of the targets of the SDGs that are closely related to the social and environmental issues associated with transport are the following: Target 3.6 of SDG 3 aims to reduce the number of global deaths and injuries from road crashes by half; Target 11.6 of SDG 11 proposes diminishing the adverse environmental consequences of cities; Target 13.2 of SDG 13 proposes the incorporation of climate change measures in national policies, strategies, and planning [5]. Sustainable urban mobility planning (SUMP) is a new strategic and integrated approach to urban transport planning. It can potentially contribute to sustainable urban mobility goals, such as air quality improvement, better accessibility, road safety improvement, traffic noise mitigation, climate change alleviation, and enhanced quality of life [6,7]. The implementation of suitable SUMP policy measures can allow the targets associated with these three to be reached.

Medium-sized cities (with less than one million people) in developing countries are residential places for approximately 25% of the global population, and those in Asian and African countries have the fastest rate of urbanization [8]. Such cities have experienced various challenges related to transport, such as adverse environmental consequences and a lack of sufficient resources [8]. Under such circumstances, medium-sized cities in developing countries critically need to appropriately prioritize and evaluate road segments according to the levels of adverse environmental consequences of their transport systems and to allocate limited budgets for the improvement of those road segments. The Central Business District (CBD) road network in Khon Kaen Metropolitan Municipality (KKMM), Khon Kaen City (KKC), Thailand, was selected as the study area. KKC, one of the largest and fastest-growing regional cities, is a medium-sized city in Thailand. With the rapid growth of its travel and freight demand, KKC has suffered from various adverse transport-related problems, such as traffic congestion, road accidents (e.g., pedestrian accident risk), adverse environmental impacts (e.g., $PM_{2.5}$ concentrations and noise levels), inefficient energy consumption, and greenhouse gas (e.g., CO_2) emissions [9]. The comprehension, prioritization, and evaluation of such transport-related environmental consequences are critical for ensuring the development of sustainable and livable cities. Based on direct interviews with decision-makers and administrators, KKMM has rarely performed suitable processes of prioritization and evaluation of all road segments according to the degrees of their separated and combined environmental consequences. An efficient decision support model (DSM) framework is indispensable in the understanding, ranking, and assessment of problematic road segments, identification of the possible causes (transport-related environmental criteria) of the problems with those road segments, and the appropriate allocation of limited budgets for their proper treatment.

The assessment of such adverse environmental effects of transport is difficult and complicated. This is because when the combined environmental effects of several road segments are estimated, multiple criteria must be simultaneously determined, and each road segment commonly experiences different levels of adverse environmental consequences (ranging from psychological effects to direct physical and health impacts) for each criterion [2]. In addition, the residents' perception (and, therefore, their relative weights) of such criteria will be altered with the road class and land use type [10,11]. Furthermore, such complex decision-making processes must normally deal with uncertain and obscure (fuzzy) information and judgments.

Generally, the evaluation of the transport-related environmental effects of each road segment is an unstructured decision-making problem involving multiple (objective and subjective) criteria: dealing with a certain number of alternatives, considering group judgments, and considering uncertain, incomplete, and ambiguous (fuzzy) information. Hence, the multiple-attribute decision-making (MADM) method matches the nature of such an evaluation [12]. Various MADM techniques have been developed, such as the simple additive weight (SAW), analytic hierarchy process (AHP), fuzzy AHP (FAHP), analytic network process (ANP), technique for order preference by similarity to an ideal solution (TOPSIS), fuzzy TOPSIS (FTOPSIS), evaluation based on distance from the average solution

(EDAS), and data envelopment analysis (DEA) [12,13]. Each of these methods is unique in terms of its potential applicability, strengths, drawbacks, and limitations.

Keshavarz-Ghorabaee [14] conducted a study to evaluate initiatives aimed at reducing air emissions from transportation by using the Stepwise Weight Assessment Ratio Analysis II (SWARA II) technique. Zarandi et al. [15] utilized the fuzzy analytic network process (FANP) to evaluate the environmental implications of $PM_{2.5}$ concentrations in Tehran, Iran. Borza et al. [16] utilized the analytic hierarchy process (AHP) and technique for order of preference by similarity to the ideal solution (TOPSIS) to conduct a multi-criterion analysis of traffic pollution at various congested intersections in Sibiu, Romania. Broniewicz et al. [17] utilized the Decision-Making Trial and Evaluation Laboratory (DEMATEL), Ratio Estimation in Magnitudes or decibels to Rate Alternatives which are Non-Dominated (REMBRANDT), and VlseKriterijuska Optimizacija I Komoromisno Resenje (VIKOR) methodologies to assess the concerns with the development of sustainable transport in association with the construction of a national road and an expressway in Northeastern Poland. Jovanovic et al. [18] performed an environmental impact assessment (EIA) using several multiple-attribute decision-making (MADM) approaches, including the AHP, AHP Entropy, TOPSIS, VIKOR, and Entropy VIKOR. Only the AHP and AHP Entropy approaches were recommended for future use in EIA. According to this concise literature review, several MADM approaches have recently been utilized in the field of EIA. A comparable pattern is anticipated for the future. The main difficulty lies in selecting the optimal combination of multiple MADM techniques for EIA and decision-making challenges, specifically for medium-sized cities in developing nations.

Recently, the hybrid MADM (HMADM), which combines various simple and beneficial algorithms, was utilized to provide more precise and better outcomes at the expense of greater difficulty and complexity [19]. In this study, the HMADM was applied to address this decision-making problem. In many HMADM studies [16,20,21], the FAHP was adopted to consider the relative weights of each criterion in a fuzzy environment but not to rank alternatives. The fuzzy scoring method (FSM) [22] can be used to transform linguistic (fuzzy) scores into corresponding numerical (crisp) scores [2,10]. TOPSIS can be applied to determine the composite scores of all alternatives when the relative weights of all criteria and the performance scores of all alternatives in association with each criterion are given. TOPSIS has been successfully applied to various domains and subject matter [23].

Although an efficient decision support model (DSM) framework is needed to rank and assess the multiple criteria of transport-related environmental effects (in a fuzzy environment) of various road segments in the urban road networks of medium-sized cities in developing countries, there is a lack of research that has attempted to perform such an important task by integrating applicable mathematical modeling methods (MMMs) for each environmental criterion with powerful HMADM techniques in a fuzzy environment. Consequently, this research aims to fill this gap by setting its main objective as the first proposal of a novel integrated DSM framework based on the combination of five robust MMM models (namely, models for the prediction of the CO concentration (COC), the CO_2 emissions (CO2Es), the $PM_{2.5}$ concentration (PM2.5C), the noise level (NOLs), and the pedestrian accident risk (PAR)) and a rigorous HMADM technique (which includes the FAHP, FSM, and TOPSIS) to efficiently prioritize and assess each separate criterion and the multiple criteria of transport-related environmental effects in the fuzzy environment of road segments in the urban road network of a medium-sized city (KKC) in a developing country (Thailand). In addition, this DSM framework can be used to identify the possible causes (transport-related environmental criteria) of problems with those road segments and to appropriately allocate limited resources for their suitable remediation.

The subsequent sections of this study are organized as follows: Section 2 presents a comprehensive literature review. Section 3 provides an overview of the materials and procedures used in this study. Section 4 presents the results and analysis. Section 5 presents the findings and proposes future research directions.

2. Literature Review

2.1. Criteria of Transport-Related Environmental Effects

Road transport is one of the main generators of various environmental effects in urban road networks [24]. Most transport vehicles utilize various fuel sources (e.g., gasoline and diesel), with electric vehicles experiencing only limited adoption [25]. The internal combustion systems of transport vehicles are the primary sources of several types of air pollution [25].

Numerous research articles (Table 1) have previously adopted multiple criteria for assessing the social and environmental effects of road transportation, including greenhouse gas (GHG) emissions, air pollution, noise pollution, and social effects.

Table 1. Urban transport social and environmental effects criteria adopted in various research studies.

Articles	GHG Emissions			Air Pollutions									Noise Pollution	Social Effects		
	CO_2	CH_4	N_2O	CO	NO_x	NO_2	SO_x	SO_2	Ozone	PM_{10} or $PM_{2.5}$	VOCs	NMVOC	Noise Levels	Road Accidents	Pedestrian Safety	Difficulty of Access
Klungboonkrong and Taylor [10]													✓		✓	✓
Singleton and Twiney [11]													✓		✓	✓
Borza et al. [16]				✓	✓				✓	✓			✓			
Chavez and Sheinbaum [26]	✓	✓	✓	✓	✓							✓				
Reisi et al. [27]													✓	✓		
Bilenko et al. [28]					✓					✓			✓			
Lokys et al. [29]						✓			✓	✓						
Luè and Colorni [30]				✓	✓								✓			
Niaz et al. [31]				✓		✓		✓								
Arroyo et al. [32]						✓			✓	✓			✓			
Saikawa et al. [33]	✓			✓	✓		✓									
Bandeira et al. [34]				✓	✓					✓			✓			
Banerjee et al. [35]				✓		✓		✓		✓						
Zapata et al. [36]				✓	✓		✓			✓						
Ugbebor and LongJohn [37]		✓		✓		✓		✓		✓			✓			
Pratama et al. [38]	✓				✓					✓						
Liu et al. [39]	✓			✓	✓					✓	✓					
Rossi et al. [40]					✓	✓				✓						
Song et al. [41]													✓		✓	
Widiantono and Samuels [42]				✓									✓	✓	✓	
Auttha et al. [43]				✓									✓		✓	
Thonnarong et al. [44]	✓									✓			✓			
Total	5	2	1	12	10	6	2	3	3	12	1	1	13	2	5	2

Several studies [45–47] indicated that PM concentrations are rising rapidly, with the majority of cases occurring in developing nations and causing significant health and environmental consequences. $PM_{2.5}$ is one of the most harmful air pollutants. The $PM_{2.5}$ concentrations measured in Bangkok, Thailand, were progressively greater than both the standard values of the World Health Organization (WHO) and the Thai National Ambient Air Quality Standards (NAAQSs) [48].

Carbon monoxide (CO) is a major air pollutant [49]. CO concentrations near the main roads in urban areas considerably exceed background levels, which could potentially be harmful to people performing activities nearby [49,50]. Several studies have found that urban road transport is responsible for more than 90% of CO emissions [49,51]. Road transport contributes approximately 50–80% of NO_2 and CO emissions in less developed countries [49,52,53]. In addition, CO can be used as an important indicator of air pollution generated by transport vehicles [49].

Greenhouse gas (GHG) emissions are widely used as critical indicators in the evaluation of the environmental effects of transport [54]. The transport sector is the second largest producer of carbon dioxide (CO_2) in Thailand after the power generation sector. It contributes approximately 26% of energy-related CO_2 emissions [55]. In addition, most CO_2 emissions are generated by road transport (approximately 97% of total CO_2 emissions from the total transport sector) [56]. Thailand ranked second in CO_2 emissions among the Southeast Asian countries [57,58].

Noise pollution is among the most pronounced environmental effects of urban transport [10]. Transport noise can have physical and psychological health consequences [59]. Recent studies [59,60] have revealed that transport noise can adversely affect people's health in ways ranging from annoyance, communication disruption, and even hearing loss. In 2020, the Pollution Control Department (PCD) [61] reported that the transport noise levels observed in 26 (96%) out of the total of 27 measured locations adjacent to urban road networks in the Bangkok Metropolitan Area (BMA) exceeded the national noise level standard (L_{eq} (24 h) = 70 dB(A) for all land use types). This finding revealed that the transport noise levels in the urban road network in the BMA are some of the most critical transport-related environmental effects in Thailand.

Klungboonkrong and Taylor [10], Singleton and Twiney [11], Song et al. [41], and the WHO [62] noted that pedestrian accident risk is a vital social and environmental issue in urban areas. In 2016, pedestrian fatalities caused by road accidents numbered approximately 1800, making up 8% of the total road fatalities in Thailand [62]. Hence, pedestrian accident risk (PAR) is one of the most critical social and environmental consequences of urban road transportation in Thailand. Although PAR is not defined as a precise environmental effect, based on the context of the area and the nature of the underlying important social and environmental issues in KKC, Thailand, the PAR criterion was selected and adopted as one of the determined criteria of transport-related social and environmental effects in this study.

As shown in Table 1, the most frequently used criteria for assessing the social and environmental effects of urban road networks, as well as the previously conducted literature review on the significance of several transport-related environmental effects in Thailand, clearly indicate that five transport-related environmental consequences (CO2E, PM2.5C, COC, NOL, and PAR) are critically important. Therefore, this study primarily focuses on these five transport-related environmental criteria.

2.2. HMADM Approach

Based on a comprehensive literature review on the applications of MADM methods to problems with urban transport sustainability, AHP, TOPSIS, and DEA were found to be the most commonly used [63]. According to a comparative analysis of MADM applications in the transport field from 2000 to 2021, AHP, TOPSIS, and Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) were found to be the most widely used MADM methods due to their universal nature, transparency, and rigorous algorithms, as well as the existence of applicable software [17]. As the determination of the relative weights of each decision criterion is one of the most vital tasks in the MADM process, the three pairwise comparison-based methods, including AHP, FAHP, and REMBRANDT, are the most pronounced and highly recommended techniques [17].

Numerous empirical investigations have demonstrated the efficacy of the FAHP in addressing a wide range of practical challenges [64,65]. Ooi et al. [64] demonstrated that the FAHP exhibited superior performance in achieving a well-rounded assessment across multiple categories that encompassed safety, health, and environmental considerations. The utilization of the FAHP enables decision-makers to enhance the realism, flexibility, and efficiency of their decision-making processes by considering the existing criteria and alternatives in an uncertain, incomplete, and ambiguous (fuzzy) environment [65]. Table 2 presents the latest scholarly articles on multicriteria decision-making techniques, with a particular emphasis on environmental criteria. The most prominent multiple-attribute decision-making (MADM) approaches in terms of theoretical and empirical investigations, as identified in a comprehensive analysis of the literature on the criteria of environmental impacts, are the FAHP, AHP, and TOPSIS.

Table 2. The application of HMADM in Sustainable transport and environmental impacts issues.

Author	Location (Year)	MADM Technique	Study Purpose
Klungboonkrong and Taylor [2]	Australia (1999)	AHP, FSM, and SAW	Spatial Intelligent Multi-Criteria Environmental Sensitivity Evaluation Planning Tool (SMESEPT) is utilized to investigate and evaluate the traffic environmental impacts evaluation of the urban road network in Geelong, Victoria, Australia.
Tuzkaya [66]	Turkey (2009)	Fuzzy AHP and PROMETHEE	In Turkey's Marma-Ra Region, an application was submitted to select the most eco-friendly mode of conveyance based on predetermined evaluation criteria.
Shelton and Medina [67]	United States (2010)	AHP and TOPSIS	Project priorities by El Paso Metropolitan Planning Organization
Ruiz-Padillo et al. [68]	Spain (2016)	Weighted sum, AHP, Elimination and Choice Translating Reality (ELECTRE), and TOPSIS	This report provides a variety of viable alternatives for reducing traffic noise on each of the road segments covered by the noise action plans.
Zečević et al. [69]	Serbia (2017)	fuzzy Delphi, fuzzy Delphi based fuzzy ANP (fuzzy DANP), and fuzzy Delphi based fuzzy Višekriterijumska Optimizacija i kompromisno Rešenje (fuzzy DVIKOR)	A framework for the selection of intermodal transport terminal (ITT) location, which would be most appropriate for the various stakeholders
Moslem et al. [70]	Turkey (2019)	Fuzzy AHP and interval AHP	Public bus transport improvement
Awasthi et al. [71]	Canada (2018)	Fuzzy TOPSIS, fuzzy VIKOR and fuzzy Gray Relational Analysis technique (fuzzy GRA)	Evaluation of urban mobility projects in Luxembourg
Hamurcu and Eren [72]	Turkey (2018)	ANP and TOPSIS	The route selection for the planned monorail transport system that is a new system in Ankara
Joo et al. [73]	Korea (2107)	AHP and Four-step simulation analysis	Developed a framework for evaluating the effectiveness of traffic calming measures (TCMs) using multiple criteria.
Borza et al. [16]	Romania (2018)	AHP and TOPSIS	To identify the most polluted and least polluted intersections based on the multiple factors considered.

Table 2. *Cont.*

Author	Location (Year)	MADM Technique	Study Purpose
Akyol et al. [74]	Turkey (2018)	Spatial multicriteria decision analysis (SMCDA) and GIS	This study utilized geographic and urbanization parameters to evaluate the environmental quality of urbanization utilized by SMCDA.
Çalık [75]	China (2019)	Fuzzy AHP and Best-Worst method (BWM)	To identify and prioritize clean air action plans for Turkey, using both imprecise and precise evaluations as a framework.
Raza et al. [76]	Pakistan (2022)	Fuzzy AHP, TOPSIS, VIKOR, and traffic simulation software (AIMSUN)	To identify the optimal solution for a more sustainable transportation system and traffic congestion reduction.
Torkayesh et al. [77]	European Countries (2022)	BWM and Measurement of Alternatives and Ranking according to the Compromise Solution (MARCOS) technique	Construct a cohesive decision model for the evaluation of air quality by considering six distinct air pollutants.
Mesa et al. [78]	Thailand (2023)	AHP and TOPSIS	Utilized to create, rank, and identify policy measure options for sustainable urban land use and transportation development.
Boru İpek [79]	Turkey (2023)	AHP and TOPSIS	Considered to integrate environmental issues in routing for pollution reduction
Aromal and Naseer [80]	India (2023)	Delphi, AHP, and TOPSIS	Prioritizing the improvement of pedestrian facilities in an urban area.
Bhardwaj and Garg [81]	China (2023)	Criteria importance through intercriteria correlation (CRITIC) and TOPSIS	To determine and assess the components of air pollution and its detrimental health effects.

The hierarchical structure of the AHP model facilitates the conceptualization of the problem by allowing users to identify all of the decision criteria, sub-criteria, and their relationships. The AHP and FAHP methods are relatively similar. However, the FAHP approach introduces a modification by transforming the AHP scale into a fuzzy environment, which enables a wide range of applications [76]. Nevertheless, individuals responsible for making decisions may experience uncertainty and ambiguity when conducting pairwise comparisons. Consequently, the FAHP was devised to assist decision-makers in addressing the inherent ambiguity and uncertainty associated with situations involving the estimation of the relative weights of criteria and the selection of alternatives [82,83]. In addition, the FSM is a rigorous technique for dealing with uncertain and unclear information and can be used to convert any linguistic (fuzzy) score into its corresponding numerical (crisp) score [2,22,43,44]. TOPSIS is a widely used and recognized technique that has been successfully applied in order to prioritize transport policy options because it is intuitive, straightforward, and accurate [12,84]. Based on a comprehensive literature review, direct comparisons of the FAHP, FSM, and TOPSIS in terms of their theoretical foundations, advantages, and disadvantages are presented in Table 3. In this research, the FAHP was adopted to estimate the relative weights of each group of transport-related environmental criteria in a fuzzy environment. This is because the theoretical foundation of the FAHP is rigorous, rational, and accurate; it can efficiently deal with group judgments, the consistency of the judgments of each expert and group of experts can be directly gauged, and it can efficiently handle the inherent fuzziness in the decision-making process [12,17,85–88]. Furthermore, the FSM was applied to transform fuzzy performance scores into crisp scores because the FSM algorithm is robust, logical, and precise, its computing procedures are simple and straightforward, and it has been successfully applied and well recognized [2,22,87]. TOPSIS was used to estimate the CTEES of each road segment. TOPSIS relies on the reliable and well-recognized theories of the ideal point technique and Euclidean distance. In addition, the TOPSIS algorithm is characterized by its rigor, logic, precision, simplicity, computational efficiency, comprehensibility, transparency, and traceability. TOPSIS has been widely applied as a powerful approach to handling practical MADM problems [12,19,60,81,82]. Consequently, in this research, the FAHP, FSM, and TOPSIS were combined to formulate a powerful HMADM approach.

Table 3. Direct comparisons of the FAHP, FSM, and TOPSIS methods.

Methods	Theoretical Foundation	Advantages	Disadvantages	Ref.
FAHP	• The fuzzy set theory (FST) allows us to take uncertain or incomplete information into account. • As the hierarchical structure is created, all criteria are paired wisely compared, using a ratio scale. • The principle of Eigen vector and Eigen value is adopted to estimate the relative weights of all criteria.	• The algorithm is accurate and rational. • Pairwise comparison is more accurate than the absolute scoring method. • The consistency of the expert's judgment can be measured directly. • The basic principle is consistent with the human decision-making process. • FAHP can tackle a group decision-making problem. • FAHP can be applied to determine both relative weights of each criterion. • Integration with other MADM techniques is possible.	• Pairwise comparisons can cause the interviewee confusion and misunderstanding. • FAHP is not suitable for the too complicated hierarchy structure when too many criteria are considered. • Judgment inconsistency and rank reversal are possible.	[12,17,85–88]
FSM	• FST can take fuzzy information into consideration. • Based on the left and right utility scoring principle, the total utility scores of each fuzzy number can be efficiently estimated.	• FSM algorithm is precise and rigorous. • The FSM can convert the fuzzy information into numerical (crisp) information. • The use of both left and right utility scores of any fuzzy number to determine its total utility scores is theoretically more accurate and robust. The computational steps of FSM are simple and straightforward.	• The numerical value is relied upon the defined dimensions of its fuzzy numbers. • Identification of appropriate fuzzy numbers is difficult, and requires professional expertise.	[2,22,87]
TOPSIS	• Based on the concept of the compromise solution by choosing the best alternative with the shortest Euclidean distance from the positive ideal solution (PIS) and the farthest Euclidean distance from the negative ideal solution (NIS).	• Algorithms are rigorous and logical. • Suitable for decision-making problems having both positive and negative criteria. • Based on the concept of ideal solutions that are reliable. • Computational procedures are straightforward and unchanged with the problem size. • TOPSIS can potentially be combined with other MADM methods.	• TOPSIS does not determine the correlation among criteria. • TOPSIS cannot be applied to quantify the relative weights of all criteria.	[12,17,23,84,89]

3. Materials and Methods

The research methodology is illustrated in Figure 1 and briefly summarized as follows:

1. **Identifying the main objectives:** The main objectives of this research were defined in this step, as described in Section 1.
2. **Literature review:** A comprehensive literature review of various research articles and reports, such as those on transport-related environmental effects and their associated MMMs, as well as several MADM and HMADM techniques.
3. **Selecting a study area:** The urban road networks of KKMM in Khon Kaen City (representing a medium-sized city), Thailand (a developing country), were selected as the study area.
4. **Selecting and interviewing experts:** Twenty human experts, including 10 urban-transport-related experts and 10 environmental experts, were selected. These 20 experts were directly interviewed to obtain their practical and professional judgments on the identification of relevant transport-related environmental criteria and on the determination of the relative weights of all selected environmental criteria for each land use type.
5. **Selecting the criteria of transport-related environmental effects:** Relying on the literature review and direct expert interviews, five criteria of transport-related environmental effects—CO2E, PM2.5C, COC, NOL, and PAR—were specified and selected.
6. **Defining performance scores:** Five performance (linguistic or fuzzy) scores of each environmental criterion were defined as very low (VL), low (L), medium (M), high (H), and very high (VH).
7. **Data collection:** On-site surveys and secondary data were collected. The following information was gathered: physical characteristics of roads, land use, demographic characteristics, meteorological data, road traffic characteristics, vehicle type specifications, and others.
8. **An integrated decision support model (DSM):** This step combined the MMM and HMADM approaches.
   - In the MMM, five applicable transport-related environmental effect prediction models, namely, the CO2E, PM2.5C, COC, NOL, and PAR models, were applied to estimate the separate CO2E, PM2.5C, COC, NOL, and PAR values of the road segments in the study area.
   - In the HMADM approach, a combination of the FAHP, FSM, and TOPSIS was adopted to calculate the composite transport-related environmental effect scores (CTEESs) for each road segment in the study area.
9. **Prioritizing road segments according to the composite scores:** The estimated CTEESs were utilized to prioritize road segments with higher levels of adverse multiple criteria environmental consequences. This prioritization of road segments can be employed to identify and rank problem locations.

3.1. Study Area

Khon Kaen City (KKC) is recognized as a hub for transport, logistics, education, medical services, social interactions, and travel, in addition to being a convention and exhibition city, low-carbon city, and smart city [90–93]. In addition, it is a strategic city in which numerous transport-related studies have been carried out [93–96]. KKMM is in the middle of KKC, Thailand. KKC is a medium-sized city in Thailand (a developing country). The CBD road network (study area) of KKC covers approximately 4 km^2. KKC is located approximately 445 km away from Bangkok. In 2019, the total population of KKMM was approximately 360,500. The general trends of the gross provincial product (GPP), employment, population, and number of registered vehicles in the KKC area from 2010 to 2019 are illustrated in Figure 2. While the total population, GPP, and number of registered vehicles gradually increased from 2010 to 2019, employment slightly fluctuated [93].

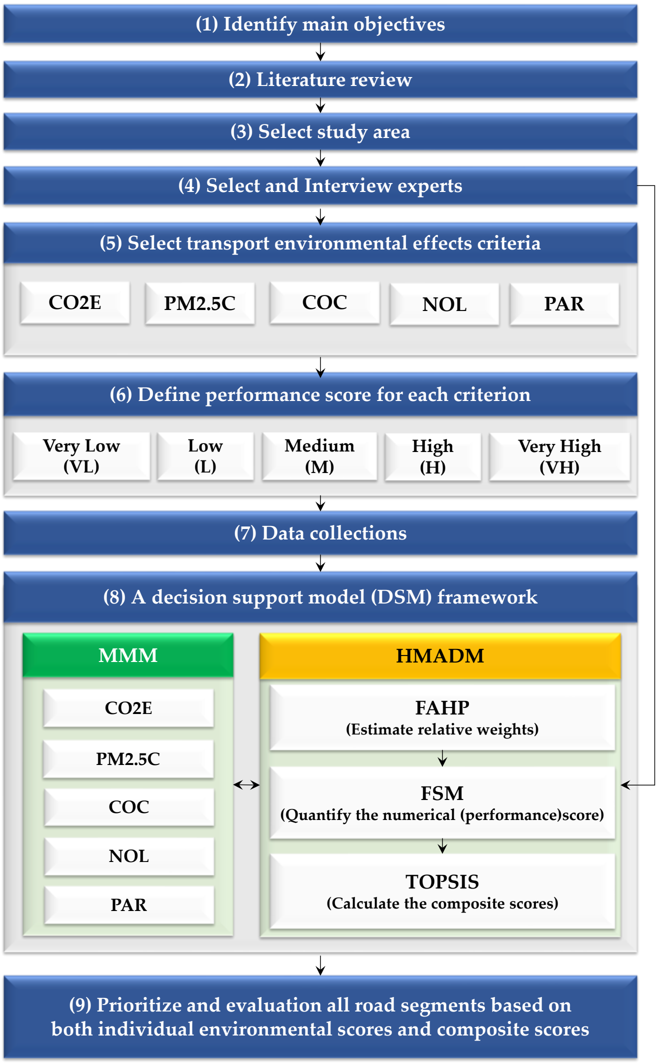


Figure 1. Research methodology.

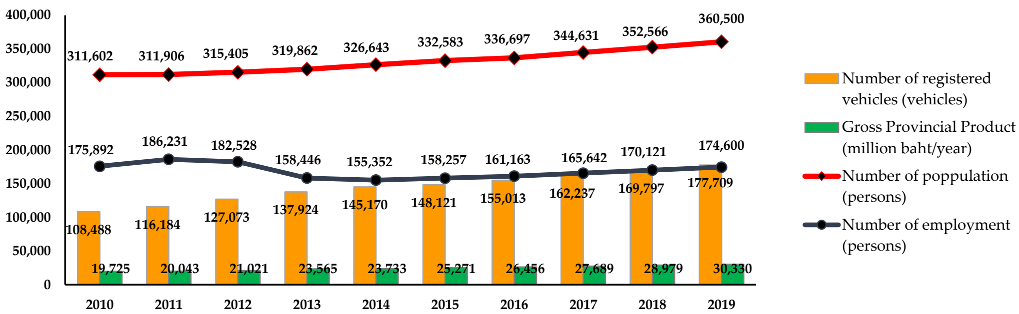
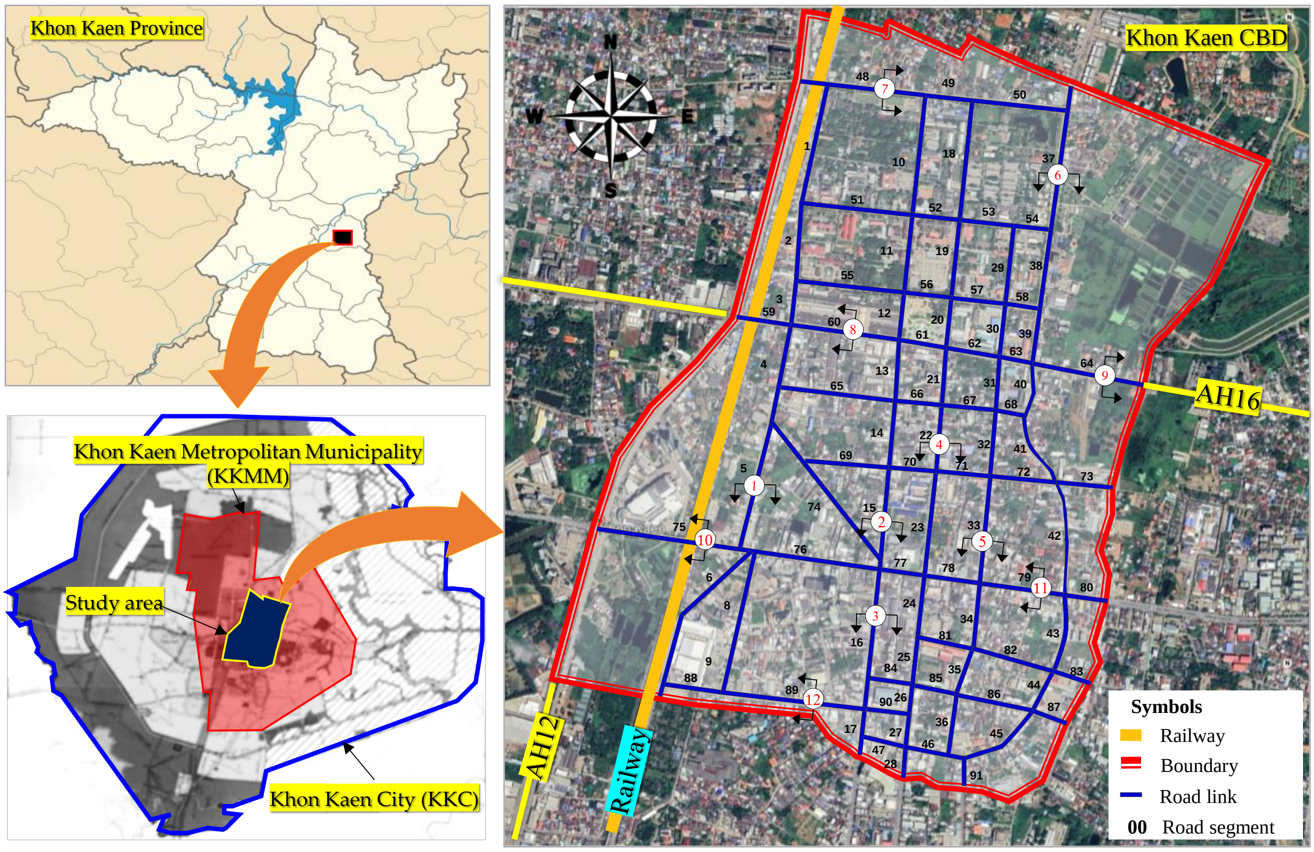
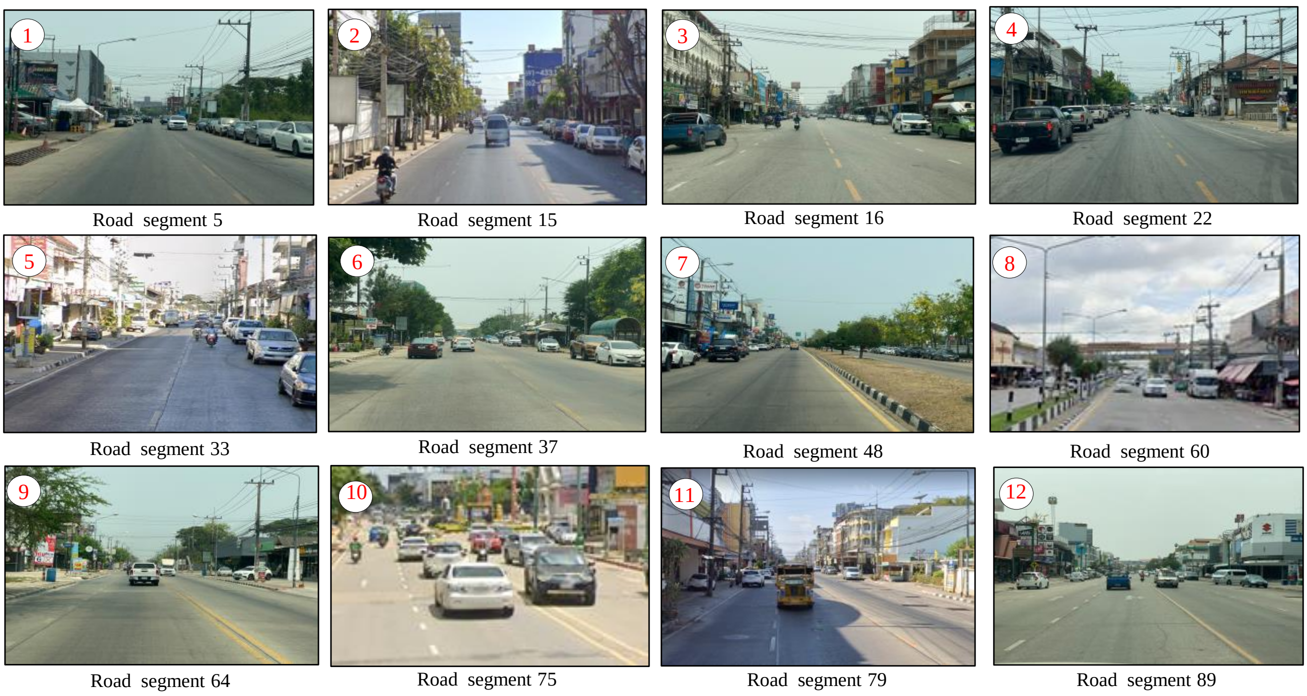


Figure 2. Trends in GPP, employment, population, and registered vehicles for the KKC area from 2010 to 2019. Adapted from Ref. [93].

Rapid growth in economic development, urbanization, land use expansion, and motorization in the area of KKMM has contributed to adverse environmental consequences in the study area, such as social severance, pedestrian accident risk, increased noise levels, air pollution, and climate change. The total length of the urban road network in the KKMM area is 452 km. The road network density of the KKMM was approximately 10 km per km^2 [97]. The road network of the CBD area in KKMM, Thailand, was selected as the study area. This road network is a grid-based system that is divided into 91 segments, as illustrated in Figure 3.



(**a**)



(**b**)

Figure 3. The geographical location map and some examples of cross-sectional characteristics of 12 road segments in the study area. (**a**) Geographical map of the study area [98]. (**b**) Examples of 12 road cross-sections in the study area.

From 1990 to 2015, there was clear evidence of rapid growth in the development of urban built-up areas (residential areas, commercial areas, and service facilities) away from the CBD [99]. This is a critical land use issue in KKC. Based on traffic and transport data collection [93], important problems related to traffic and transport are traffic congestion, road accidents, and inefficient public transport systems (such as unsafe services, excessive travel times, and delays). For general road traffic, excessive mean delays and long queue lengths were observed at several intersections during peak hours. Furthermore, the average operating speeds during peak hours on most roads in the Khon Kaen Central Business District (CBD) are below 10 km/h [93].

3.2. Selection of Experts and Interviews

In this research, 20 human experts were carefully selected and were equally divided into two groups: (1) the "urban land use and transport planning" experts and (2) the "environmental" experts. These experts were chosen based on the following criteria: (1) Each expert needed to be directly involved in at least one urban land use and transport planning and development project in Thailand, and (2) each expert needed to have practical and professional experience and expertise related to the assessment of urban-transport-related environmental impacts in Thailand. These 20 experts were directly interviewed to acquire practical and professional judgments regarding the selection of suitable transport-related environmental criteria and the determination of the relative weights of these selected criteria for each land use type in the study area. This study was approved by the Human Research Ethics Committee of Khon Kaen University (No. HE653282).

3.3. Data Collections

In this study, only the main arterials and important collector roads in the CBD road network of KKMM in Khon Kaen City, Thailand, were determined. Considerable amounts of input data that were required for the five selected MMMs were collected. Examples of the data collection for several road segments are presented in Table 4. The following data were gathered: (1) the physical and land use characteristics of roads (e.g., road classes, road lengths, land use types, etc.), (2) road traffic characteristics (e.g., peak hourly traffic volumes, average speeds, vehicle composition, etc.), (3) information on the topography and built environment (e.g., building set-back distance, road gradients, etc.), (4) vehicle type specifications (e.g., the typical vehicle engine power, emission factors of each vehicle and engine type, etc.), (5) meteorological data (e.g., wind speed and direction, temperature, etc.), and others [9,93].

Table 4. Some examples of the on-site surveyed and secondary collected data [9,93].

Items	No. of Road Segments	Land Use Type	Number of Lanes	Segment Lengths (m)	Effective Road Width (m)	Building Setback from the Centerline of a Road (m)	Average Speeds (km/h)	Peak Hourly Flows (veh/h)	Heavy Vehicle Composition (%)
1	5	2	2	660.10	10.66	8.16	20.1	2134	4
2	15	1	4	270.15	12.68	10.18	27.1	1828	5
3	16	2	4	550.20	12.87	10.37	22.3	1946	5
4	22	2	2	270.40	10.89	8.39	23.8	2051	4
5	33	1	2	300.30	8.46	5.96	23.7	749	5
6	37	2	4	580.40	14.56	8.28	30.5	1831	4
7	48	2	6	470.35	19.49	11.17	20.4	3068	5
8	60	2	6	420.25	14.82	15.30	21.3	3210	4
9	64	1	4	430.40	11.51	7.35	17.2	3428	4
10	75	2	4	550.30	12.75	8.25	24.5	5380	3
11	79	1	4	240.25	17.40	14.90	15.0	3440	4
12	89	2	4	560.05	17.67	10.96	23.6	2218	9

Notes: Land use type 1 (e.g., residential areas, schools, hospitals, etc.) and land use type 2 (e.g., retailing shops, commercial areas, business offices, etc.).

In this research, most of the traffic-related data (e.g., peak hourly traffic flows, heavy-vehicle composition, and average speeds) of each road segment in the study area were obtained through the Development of Multimodal Travel Demand Model (MTDM) task in a study of the detailed design of the public transport system and an environmental impact assessment (EIA) in Khon Kaen City [93,100]. The validation results of the MTDM clearly illustrated that the modeled transport demands fit reasonably well with the surveyed data, with an average root mean square (RMS) error of 5.5% [93], suggesting that the developed MTDMs could reasonably be used to predict travel demands in this study.

3.4. An Integrated Decision Support Model (DSM) Framework

An integrated DSM involving a combination of MMMs for prediction and the HMADM approach was initially proposed to determine the multiple criteria of transport-related environmental effects of all road segments in the urban road network in the study area. Five MMMs, namely, the CO2E [54,91], PM2.5C [54,91,101], COC [54,91,101], NOL [102], and PAR models [41], were adopted to estimate the CO2E, PM2.5C, COC, NOL, and PAR values for each road segment in the study area. In the HMADM method, the FAHP, FSM, and TOPSIS were integrated to prioritize road segments according to their estimated composite scores. The FAHP was used to calculate the relative weights of each environmental criterion for each land use type, and the FSM was applied to transform the performance (linguistic or fuzzy) scores into numerical (crisp) scores. Finally, TOPSIS was adopted to estimate the composite transport-related environmental effect scores (CTEESs) of all road segments in the study area. The integrated DSM framework was used to comprehend and evaluate both the individual environmental criteria and the multiple environmental criteria of each road segment in the urban road network of the study area.

Mathematical Modeling Methods (MMMs)

Five MMMs for prediction were applied to determine the individual transport-related environmental effects of the CO2E, PM2.5C, COC, NOL, and PAR criteria. The models are briefly summarized in the following.

- CO2E, PM2.5C, and COC prediction models

CO2E values can be computed by using the bottom-up 2 method [9,54]. PM2.5C and COC values can also be calculated by using the bottom-up 2 method [9,54] in association with the Delhi finite line source model (DFLSM) [101]. The bottom-up 2 method was used to estimate the amounts of CO_2, $PM_{2.5}$, and CO emissions for each road segment by considering the traffic volumes, emission factors for each vehicle and engine type, and road distance [9,54,91,103]. The computational steps of the bottom-up 2 technique are illustrated in Figure 4. Based on this method, the total amounts of CO_2, $PM_{2.5}$, and CO emissions for each road segment can be estimated by using Equation (1) [54].

$$TE_e = \sum_i \sum_j (EF_{ij} \times L_e \times Q_{ije}) \quad (1)$$

where TE_e = the total emissions from all vehicle types i and engine types j on a road segment (e), EF_{ij} = the emission factors of vehicle type i and engine type j, L_e = the length of a road segment (e), Q_{ije} = the traffic volume of vehicle type i and engine type j on a road segment (e).

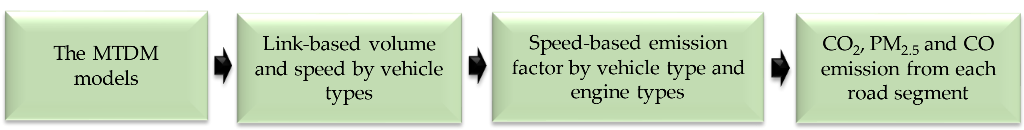


Figure 4. Computational steps for the bottom-up 2 method for the estimations of the CO_2, $PM_{2.5}$, and CO emissions of each road segment. Adapted from Ref. [54].

Subsequently, the DFLSM [101] was utilized to estimate the concentrations of both $PM_{2.5}$ and CO for each road segment. Only CO_2 emissions were determined in this study. Five common vehicle types operating in the study area were considered in: motorcycles (MCs), passenger cars (PCs), pick-up trucks (PUTs), buses (Bs), and trucks (Ts) [9,54]. Hence, the CO_2, CO, and $PM_{2.5}$ emission factors associated with these vehicle types and engine types were utilized and are presented in Table 5.

Table 5. The CO_2, CO, and $PM_{2.5}$ emission factors by vehicle types and fuel types [104].

Vehicle Types	Emission Factors					
	CO_2	R^2	CO	R^2	$PM_{2.5}$	R^2
Motorcycles (MCs)	$Y = 0.0022\ V^2 - 0.3678\ V + 43.047$	0.98	$Y = -1 \times 10^{-4}\ V^2 + 0.0188\ V + 2.233$	0.99	-	-
Passenger cars (PCs)	$Y = 0.0289\ V^2 - 4.4627\ V + 276.82$	0.97	$Y = 3 \times 10^{-5}\ V^2 - 0.0042\ V + 0.3662$	0.98	-	-
Pick-up trucks (PUTs)	$Y = 0.0361\ V^2 - 5.6159\ V + 363.97$	0.97	$Y = 0.0003\ V^2 - 0.0367\ V + 1.5975$	0.94	$Y = 5 \times 10^{-6}\ V^2 - 0.0008\ V + 0.0829$	0.98
Buses (Bs)	$Y = 0.265\ V^2 - 35.016\ V + 1714.4$	0.97	$Y = 0.0014\ V^2 - 0.1867\ V + 7.47$	0.94	$Y = 0.0001\ V^2 - 0.0141\ V + 1.2356$	0.99
Trucks (Ts)	$Y = 0.2593\ V^2 - 34.262\ V + 1671.7$	0.97	$Y = 0.001\ V^2 - 0.1382\ V + 6.309$	0.96	$Y = 4 \times 10^{-5}\ V^2 - 0.0044\ V + 0.487$	0.98

Notes: V = average operating speed (km/h), and Y = CO_2, CO, and $PM_{2.5}$ emission factors (g/km).

- Noise level (NOL) prediction models

The calculation of road traffic noise (CORTN) method [102], which was initially introduced by the Department of Transport of the United Kingdom (UK), has been recognized as one of the most applicable and acceptable urban transport noise level (TNL) models. Based on statistical comparisons between the measured and estimated urban TNL values, the accuracy of the CORTN model was satisfactory [59,105]. The CORTN model relies on the use of charts and graphs (including numerous empirical equations) for simple and straightforward computing procedures [106]. Consequently, CORTN was adopted in this study. The procedural steps for calculating the TNL values of a road segment based on the CORTN methodology are illustrated in Figure 5.

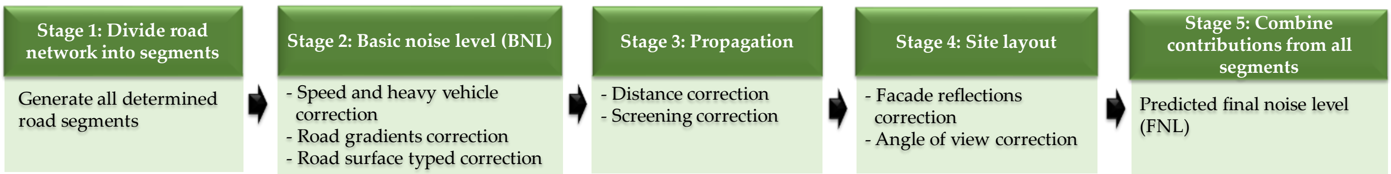


Figure 5. A flow chart showing the CORTN procedural steps for calculating TNL of a road segment. Adapted from Ref. [102].

The basic noise level (BNL) can be computed by using Equation (2) [102]:

$$L_{10}(18\text{ h}) = 29.1 + 10log_{10}Q \quad (2)$$

where Q = the traffic volume over 18 h (from 6 a.m. to midnight).

Once the BNL of each road segment was estimated, a series of corrections were applied to achieve the final noise level (FNL) of each. In this research, several corrections were considered for the following aspects: (i) speed and heavy vehicles (C_{sh}); (ii) road gradient (C_g); (iii) road surface type (C_{rs}); (iv) distance of attenuation (C_d); (v) screening corrections (C_s); (vi) angle of view (C_a); (vii) facade reflection (C_r) [102]. The *FNL* can be calculated by using Equation (3):

$$FNL = BNL + \sum_{i=1}^{n} C_i \quad (3)$$

- Pedestrian accident risk (PAR)

The statistical model initially introduced by Song et al. [41] was used to determine the pedestrian accident risk for each urban road segment in the study area. Song's model [41] is a behavioral probabilistic model based on Bayes' theory. This analytical model appears to be the most appropriate for predicting mid-block pedestrian accident risk in urban road networks in Australia. It has been used in several studies conducted in Australia [2,41] and Thailand [10,43]. The pedestrian accident risk derived from Song's model [41] is given in Equation (4).

$$PAR = 1.851(1 - e^{-Q\alpha}) \times Q^{0.713} \times V^{0.733} \times t^{0.523} \times 10^{-6} \quad (4)$$

where Q is the traffic flow (vehicles/s), V is the operating speed (m/s), t is the crossing time (s), and α is the critical gap (s). Given the values of Q, α, V, and t, PAR can be calculated accordingly.

3.5. The HMADM Technique

In this study, the HMADM technique was applied to evaluate the multicriteria transport-related environmental consequences of urban road networks (at a link-based level). Here, it comprised three powerful MADM methods: the FAHP, FSM, and TOPSIS.

3.5.1. Fuzzy Set Theory (FST)

The FST, which was first introduced by Zadeh [107], is used to deal with uncertain, incomplete, and ambiguous (fuzzy) information. It is intended to generalize and relax the theoretical rigidity of traditional set theory (TST).

3.5.2. Fuzzy Analytic Hierarchy Process (FAHP)

Van Laarhoven and Pedrycz [108] first introduced the FAHP technique in 1983, which involves the utilization of triangular fuzzy numbers (TFNs) within a pairwise comparison matrix [108,109]. The adoption of fuzzy numbers within an FAHP entails the representation of a continuum of potential values associated with a given variable or rating. TFNs are commonly used in FST because of their ease of mathematical calculation and operation in fuzzy environments [110]. TFNs are denoted by a triplet of numerical values (l, m, u), where l, m, and u represent the minimum, most probable, and maximum conceivable values, respectively [111]. The mathematical expression for a fuzzy number A, which is characterized by its membership function $\mu_A(x)$, is shown in Equation (5) and Figure 6a, as illustrated in the work of Alyamni and Long [112].

$$\mu_A(x) = \begin{cases} 0 & x < l; \\ \frac{x-l}{m-l} & l \le x \le m; \\ \frac{u-x}{u-m} & m \le x \le u; \\ 0 & x > u. \end{cases} \quad (5)$$

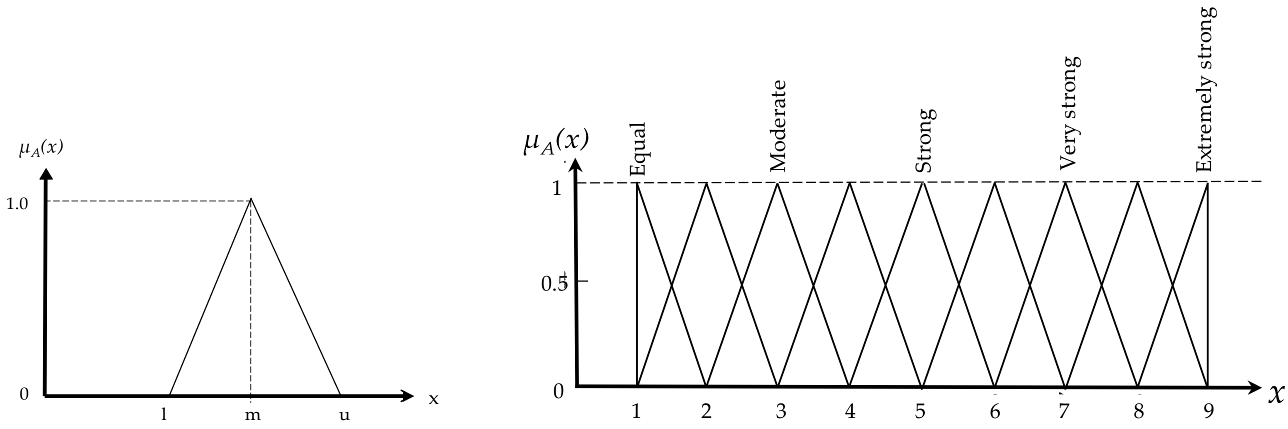
In this research, the FAHP was applied to estimate the relative weights of each environmental criterion. The TFNs corresponding to the nine-point scaling scheme established by Kannan et al. [82], as presented in Figure 6b, were utilized for this objective.

The relative weight of each environmental criterion was calculated by using Chang's technique [113]. The basic principle of the FAHP for computing the numerical (crisp) weights of TENs is as follows:

Step 1: Define the problem and determine the desired solution.

First, establish a hierarchical structure based on the decision criteria identified previously.

Step 2: Perform pairwise comparisons.



(**a**) (**b**)

Figure 6. The membership function of TFNs corresponding to the nine-point scaling scheme. [82,112]. (**a**) The membership function of a TFNs. (**b**) The TFNs corresponding to the nine-point scaling scheme.

In this step, each expert is asked to generate a pairwise comparison matrix of all determined criteria by using linguistic (TFN) scales. The resulting comparison matrix $\widetilde{D} = \left[\widetilde{a}_{ij}\right]$ is expressed in Equation (6).

$$\widetilde{D} = \begin{pmatrix} (1,1,1) & \widetilde{a}_{12} & \cdots & \widetilde{a}_{1n} \\ \widetilde{a}_{21} & (1,1,1) & \cdots & \widetilde{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \widetilde{a}_{n1} & \widetilde{a}_{n2} & \cdots & (1,1,1) \end{pmatrix} \tag{6}$$

where $\widetilde{a}_{ij} = (l_{ij}, m_{ij}, u_{ij}), i, j = 1, 2, \ldots, n$.

In the context of the FAHP, the entire pairwise comparison matrix was created by using TFNs denoted as the l, m, and u elements, as described previously. This approach was used when numerous experts participated in the decision-making process.

Step 3: The fuzzy synthetic extent with respect to criterion i (Si) for the pairwise evaluation matrix is calculated.

Si is defined as shown in Equation (7).

$$Si = \sum_{j=1}^{m} M_{g_i}^{j} \otimes \left[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{gi}^{j}\right]^{-1} \tag{7}$$

The variables "i" and "j" represent the row and column numbers, respectively. In Equation (9), M_{gi}^{j} denotes the TFNs of the pairwise comparison matrices. The terms $\sum_{j=1}^{m} M_{g_i}^{j}$, $\sum_{i=1}^{n}\sum_{j=1}^{m} M_{g_i}^{i}$, and $\left[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{g_i}^{j}\right]^{-1}$ can be calculated by using Equations (8), (9), and (10), respectively.

$$\sum_{j=1}^{m} M_{g_i}^{j} = \left(\sum_{j=1}^{m} l_j, \sum_{j=1}^{m} m_j, \sum_{j=1}^{m} u_j\right) \tag{8}$$

$$\sum_{i=1}^{n}\sum_{j=1}^{m} M_{g_i}^{j} = \left(\sum_{i=1}^{n} l_i, \sum_{i=1}^{n} m_i, \sum_{i=1}^{n} u_i\right) \tag{9}$$

$$\left[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{g_i}^{j}\right]^{-1} = \left(\frac{1}{\sum_{i=1}^{n} u_i}, \frac{1}{\sum_{i=1}^{n} m_i}, \frac{1}{\sum_{i=1}^{n} l_i}\right) \quad (10)$$

where l_j, m_j, and u_j denote the minimum, most probable, and maximum values of i elements, respectively.

Step 4: Calculation of the best non-fuzzy performance (BNP) value.

The defuzzification procedure involves considering the best nonfuzzy performance (*BNP*) value, the fuzzy weight of a criterion, and the subsequent computation of the *BNP* value of the ultimate weight [114].

$$BNP_{Si} = \frac{[(u_{Si} - l_{Si}) + (m_{Si} - l_{Si})]}{3} + l_{Si}; where\ i = (1,2,3,4,5) \quad (11)$$

where BNP_{Si} denotes the best non-fuzzy performance value (crisp weights) for each criterion.

BNP values can be utilized to establish the priority of relative importance among criteria, whereby the criterion possessing the greatest *BNP* is designated as the most important, and the criterion with the smallest *BNP* is regarded as the least important [115].

Step 5: Consistency test of the comparison matrix.

The consistency index (CI) was computed by using an equation (CI = (λ_{max} − n)/(n − 1)) to measure the consistency of the square matrix A. The ratio between the CI and RCI (displayed in Table 6) is referred to as the consistency ratio (CR) [116]. In general, a CR less than or equal to 0.10 is acceptable; otherwise, square matrix A is adjusted to improve judgment consistency [85]. The normalization of the geometric mean of the row (NGM) [117] was applied to determine the relative weights of all criteria and to calculate the largest eigenvalue (λ_{max}) of the square matrix A to facilitate numerical computations [117]. The geometric mean method (GMM) was used to combine individual judgments into group judgments [118].

Table 6. Random consistency index (RCI) [116].

n	1	2	3	4	5	6	7	8	9
RCI	0.00	0.00	0.52	0.89	1.11	1.25	1.35	1.40	1.45

3.5.3. Fuzzy Scoring Method (FSM)

Chen and Hwang [22] developed an FSM for transforming linguistic (fuzzy) scores into their corresponding numerical (crisp) scores. It employs a left-and-right scoring method to calculate the total utility score for each fuzzy number. The fuzzy max and fuzzy min in the FSM are defined in Equations (12) and (13), respectively.

$$\mu_{max}(x) = \begin{cases} x, 0 \le x \le 1, \\ 0, otherwise, \end{cases} \quad (12)$$

$$\mu_{min}(x) = \begin{cases} 1 - x, 0 \le x \le 1, \\ 0, otherwise, \end{cases} \quad (13)$$

After defining the fuzzy max and min, the absolute numerical values of the fuzzy numbers can be efficiently determined. The left ($\mu_L(i)$) and right utility scores ($\mu_R(i)$) of such a fuzzy number (M_i) can be estimated by using Equations (14) and (15), respectively [22]. Given the left and right utility scores, Equation (16) can be used to estimate the total utility score ($\mu_T(i)$) of M_i [22].

$$\mu_L(i) = \sup_x[\mu_{min}(x) \wedge \mu_{Mi}(x)] \quad (14)$$

$$\mu_R(i) = \sup_x[\mu_{max}(x) \wedge \mu_{Mi}(x)] \quad (15)$$

$$\mu_T(i) = \frac{[\mu_R(i) + 1 - \mu_L(i)]}{2} \tag{16}$$

3.5.4. Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS)

Hwang and Yoon [119] developed TOPSIS, which is one of the most widely used MADM techniques. TOPSIS is based on the fundamental concept that the best alternative will have the minimum separation from the positive ideal solution (PIS) and the maximum separation from the negative ideal solution (NIS) according to the measurement of the relative separation between each alternative and the optimal solution by using the Euclidean distance [120]. Both the separation (S_i^+) of each alternative from the PIS and the separation (S_i^-) of each alternative from the NIS are determined by using TOPSIS. The alternative priority (A_i) can be determined by comparing the relative closeness (C_i) [121]. Because of its simplicity, ease of use, comprehensibility, computational efficiency, flexibility, transparency, and traceability in examining the performance of all determined alternatives, TOPSIS has been widely applied as a powerful technique for addressing practical MADM problems [115,116]. The calculation stages of TOPSIS (Figure 7) are described in detail below.

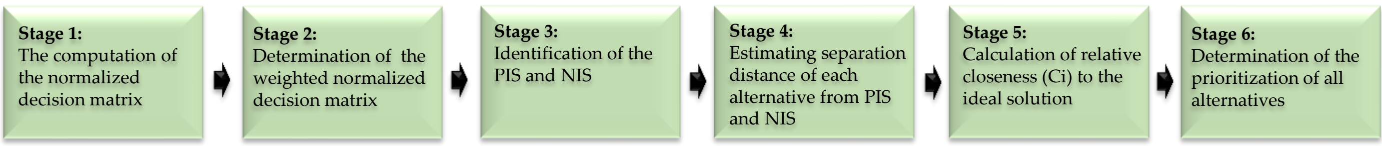


Figure 7. Procedures of the TOPSIS. Adapted from Ref. [120].

Stage 1: A normalized decision matrix, where the normalized value (r_{ij}) is determined by using Equation (17), is estimated; f_{ij} is the performance rating of the i^{th} alternative according to the j^{th} criterion, i is the number of alternatives, n is the total number of alternatives to be analyzed, j is the criterion, and m is the total number of determined criteria.

$$r_{ij} = \frac{f_{ij}}{\sqrt{\sum_{i}^{n} f_{ij}^2}}; i = 1, 2, \ldots n; j = 1, 2, \ldots m. \tag{17}$$

Stage 2: A weighted normalized decision matrix in which the weighted normalized value v_{ij} is computed according to Equation (18) is estimated; w_j denotes the weight of the j^{th} criterion.

$$v_{ij} = w_j \times r_{ij}; i = 1, 2, \ldots, n; j = 1, 2, \ldots, m \tag{18}$$

Stage 3: The PIS and NIS are determined by using Equations (19) and (20), respectively, where J_1 is associated with advantageous characteristics (i.e., the greater the value, the better the performance). J_2 is associated with disadvantageous characteristics (i.e., the lower the value, the better the performance).

$$V_j^+ = \{(maxv_{ij}|j \in J_1), (minv_{ij}|j \in J_2), i = 1, 2, \ldots, m\} \tag{19}$$

$$V_j^- = \{(minv_{ij}|j \in J_1), (maxv_{ij}|j \in J_2), i = 1, 2, \ldots, m\} \tag{20}$$

Stage 4: The separation between either the PIS or NIS and each alternative is determined. The Euclidean distance is utilized to calculate the separation values, and Equation (21) is used to compute the distance between each alternative and the PIS. Similarly, Equation (22) computes the separation from the NIS.

$$S_i^{+} = \sqrt{\sum_{j=1}^{m} \left(v_{ij} - V_j^{+}\right)^2}; i = 1, 2, \ldots, n; j = 1, 2, \ldots, m \quad (21)$$

$$S_i^{-} = \sqrt{\sum_{j=1}^{m} \left(v_{ij} - V_j^{-}\right)^2}; i = 1, 2, \ldots, n; j = 1, 2, \ldots, m \quad (22)$$

Stage 5: The relative closeness (C_i) to the ideal solution can be derived by using Equation (23):

$$C_i = \frac{S_i^{-}}{S_i^{+} + S_i^{-}}, i = 1, 2, 3, \ldots, n \quad (23)$$

Stage 6: To determine the best alternative, the relative closeness (C_i) of each alternative to the ideal solution is used to determine its prioritization. The best alternative has the shortest distance from the PIS and the longest distance from the NIS [122]. The greater the relative closeness (C_i), the better the alternative.

4. Results

4.1. The MMM Results

Based on previous studies [3,40,44,45], the performance scores of the five environmental criteria were classified into five levels: "very low (VL)", "low (L)", "medium (M)", "high (H)", and "very high (VH)", as shown in Table 7. If road segments were identified as having "very high (VH)" or "high (H)" scores for any of the environmental criteria, this indicated that they required immediate attention and investigation to specify the possible causes of these very high or high degrees of transport-related environmental effects problems according to those criteria. In contrast, if road segments were specified as having "very low (VL)" or "low (L)" scores for any criteria, this meant that they experienced very low or low degrees of transport-related environmental consequences according to those criteria. If road segments were specified as having "medium (M)" scores for any criteria, this indicated that they moderately suffered from transport-related environmental effects according to those criteria. The meticulous analysis outlined in Section 4.4 was used to identify the significant factors contributing to the transport-related environmental effects in the segments according to the determined criteria.

Table 7. The classification of the performance scores for each transport environmental criterion.

Criteria	Units	Performance Scores					Ref.
		Very Low (VL)	Low (L)	Medium (M)	High (H)	Very High (VH)	
CO2E	kg/h	0–17	17–38	38–92	92–235	>235	[100]
PM2.5C	μg/m^3 (24-h)	0–25	26–37	38–50	51–90	>90	[123]
COC	ppm (8-h)	0.0–4.4	4.5–6.4	6.5–9.0	9.1–30.0	>30.0	[123]
NOL	L_{eq} (24 h) dB (A)	0.0–60.0	60.1–65.0	65.1–70.0	70.1–75.0	>75	[124]
PAR	-	(0.0–0.5) × 10^{-5}	(0.5–1) × 10^{-5}	(1–2) × 10^{-5}	(2–2.5) × 10^{-5}	>2.5 × 10^{-5}	[10,41,43]

Note: CO2E using cluster analysis for classified performance scores.

Figure 8 depicts the geographical distribution of all performance scores, which represent the transport-related environmental effects score (TEES) values of all 91 road segments for each of the five environmental criteria. For each criterion, all road segments with "very high" and "high" scores for any criterion were determined as potentially problematic locations according to that criterion.

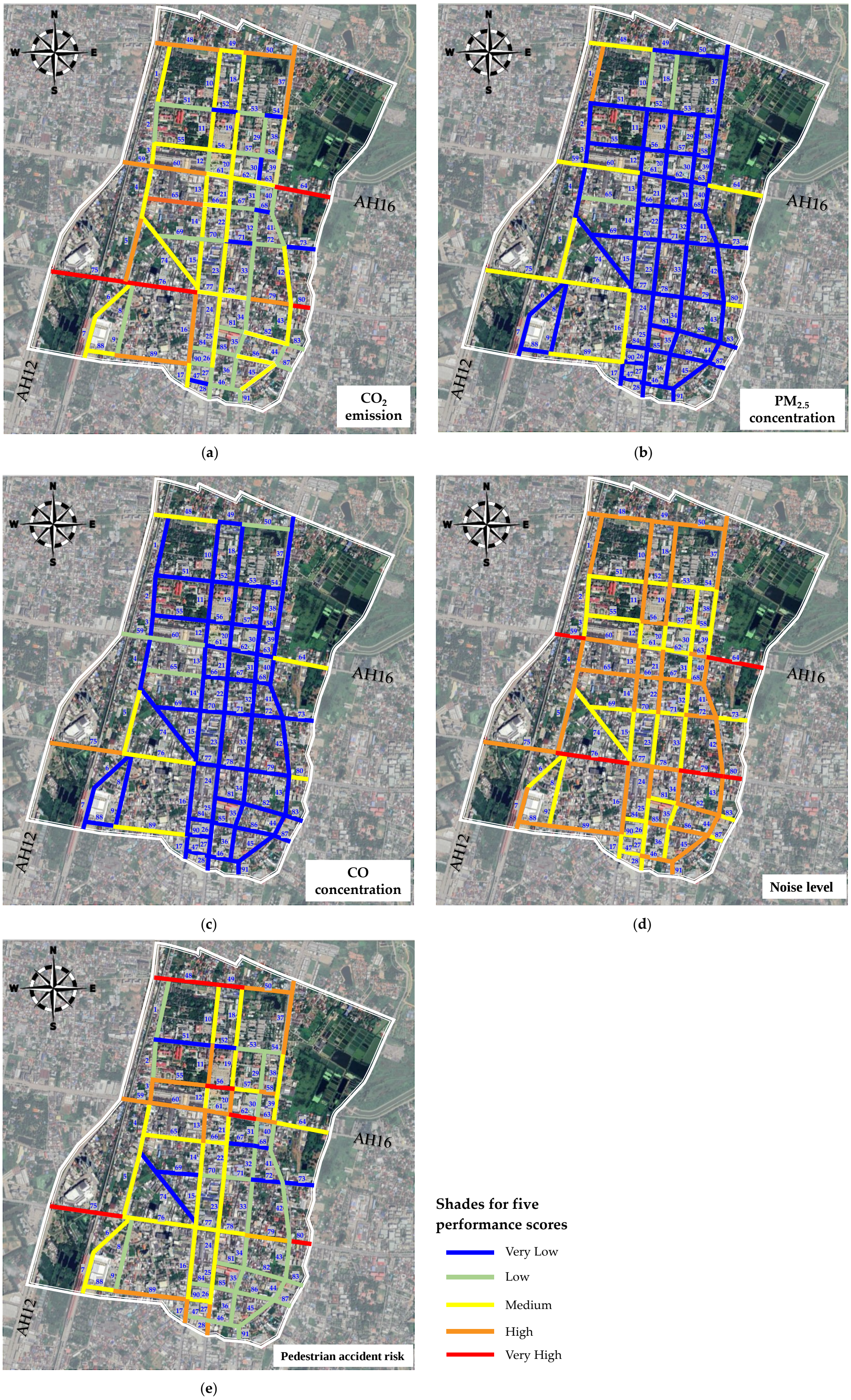


Figure 8. The transport environmental effects scores (TEES) for five criteria [98]. (**a**) TEES for CO2E. (**b**) TEES for PM2.5C. (**c**) TEES for COC. (**d**) TEES for NOL. (**e**) TEES for PAR.

4.2. Determination of the Relative Weights of All Criteria by Using the FAHP

4.2.1. Organizing Decision Elements into a Hierarchical Structure

As depicted in Figure 9, all of the environmental criteria, namely, CO2E, COC, PM2.5C, NOL, and PAR, were designated, and their relationships were arranged hierarchically. The hierarchical structure consisted of three main levels: level 1 (the key objective), level 2 (five selected environmental criteria), and level 3 (91 road segment options). Between levels 1 and 2, 20 experts were directly interviewed to gain their knowledge and expertise regarding the relative weights of all transport-related environmental criteria for each land use type. Between levels 2 and 3, the five selected mathematical models were applied to estimate the CO2E, COC, PM2.5C, NOL, and PAR values of each road segment option. Subsequently, the estimated transport-related environmental effect values of each road segment option for each criterion were categorized into five performance scores (VL, L, M, H, and VH) according to the classification system that was defined in Table 8. Given the relative weights of all environmental criteria for each land use type and the assigned performance scores of all road segment options for each criterion, TOPSIS was applied to calculate the CTEESs of all road segment options, as will be described in Section 4.4. Typically, residents' perceptions and attitudes toward each transport-related environmental criterion and, therefore, their corresponding relative weights of such criteria vary with land use types [2,11]. To determine the CTEES of each road segment, the relative weights of all selected transport-related environmental criteria for each land use type needed to be appropriately quantified. Based on the degree of sensitivity to such adverse transport-related environmental effects [2,11,43], in this study, the land uses in the study area were classified into three main types: (1) land use type I (e.g., residential areas, colleges, and hospitals); (2) land use type II (e.g., retail stores, commercial areas, business offices); (3) land use type III (e.g., industrial areas, railway stations, and transit terminals). Land use types I, II, and III were considered "highly sensitive", "moderately sensitive", and "less sensitive" to transport-related environmental consequences, respectively.

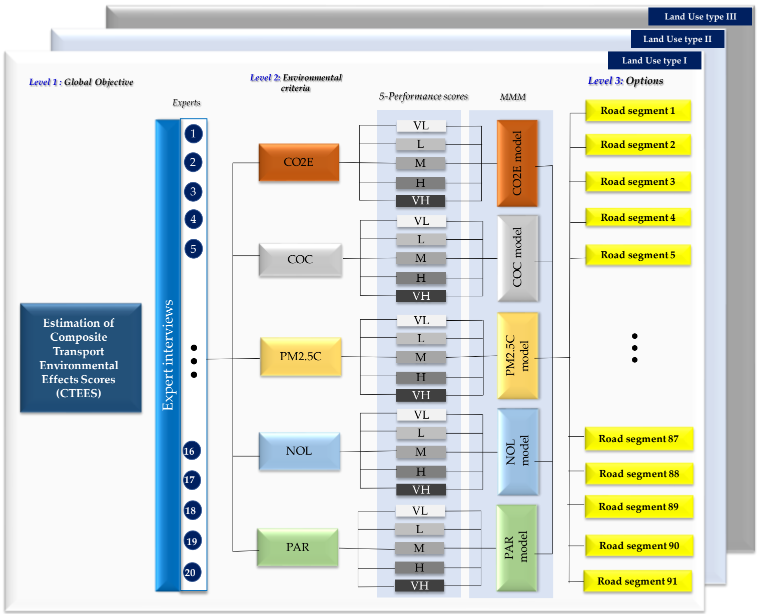


Figure 9. The FAHP hierarchical structure.

4.2.2. Estimations of the Relative Weights of All Criteria

After identifying the five environmental criteria, 20 experts were asked to provide their judgments on the relative weights of each environmental criterion by conducting pairwise comparisons with a nine-point ratio scaling system in a fuzzy environment. Table 8 provides examples of the pairwise comparisons of the criteria considered by one of the 20 chosen experts. Because there were 20 experts, the geometric mean of the TFNs corresponding to the linguistic expressions was determined. The relative weights of the criteria were obtained by using subsequent computations. A pairwise comparison matrix of all of the environmental criteria for "land use type I" from the group of 20 experts is shown in Table 9.

Table 8. An example of the pairwise comparisons of all criteria for "Land use type I" from one expert.

Criteria	C1	C2	C3	C4	C5
CO_2 emission (C1)	(1, 1, 1)	(1/4, 1/3, 1/2)	(1/3, 1/2, 1)	(1/6, 1/5, 1/4)	(1/8, 1/7, 1/6)
$PM_{2.5}$ concentration (C2)	(2, 3, 4)	(1, 1, 1)	(1, 2, 3)	(1/3, 1/2, 1)	(1/5, 1/4, 1/3)
CO concentrations (C3)	(1, 2, 3)	(1/3, 1/2, 1)	(1, 1, 1)	(1/5, 1/4, 1/3)	(1/6, 1/5, 1/4)
Noise levels (C4)	(4, 5, 6)	(1, 2, 3)	(3, 4, 5)	(1, 1, 1)	(1/4, 1/3, 1/2)
Pedestrian accident risk (C5)	(6, 7, 8)	(3, 4, 5)	(4, 5, 6)	(2, 3, 4)	(1, 1, 1)

Note: λ_{max} = 5.1289, CI = 0.0322, and CR = 0.0290.

Table 9. An example of the pairwise comparisons of all criteria for "Land use type I" from a group of 20 experts.

Criteria	C1	C2	C3	C4	C5
CO_2 emission (C1)	(1, 1, 1)	(0.399, 0.513, 0.687)	(0.563, 0.738, 1.031)	(0.338, 0.416, 0.532)	(1.730, 2.515, 3.350)
$PM_{2.5}$ concentration (C2)	(1.455, 1.949, 2.503)	(1, 1, 1)	(1.206, 1.628, 2.216)	(0.602, 0.777, 1.034)	(3.532, 4.263, 4.941)
CO concentrations (C3)	(0.970, 1.356, 1.775)	(0.451, 0.614, 0.829)	(1, 1, 1)	(0.308, 0.403, 0.548)	(2.505, 3.262, 4.114)
Noise levels (C4)	(1.879, 2.401, 2.960)	(0.967, 1.287, 1.661)	(1.824, 2.480, 3.243)	(1, 1, 1)	(4.074, 5.019, 5.872)
Pedestrian accident risk (C5)	(0.299, 0.398, 0.578)	(0.202, 0.235, 0.283)	(0.243, 0.307, 0.399)	(0.170, 0.199, 0.245)	(1, 1, 1)

Note: λ_{max} = 5.0203, GCI = 0.0051, and GCR = 0.0046.

It was essential to calculate the fuzzy relative weights or fuzzy synthetic extents (Si) for all five environmental criteria when determining their relative weights. The defuzzification method outlined in Equation (7) was used to address the fuzziness of the weights. The goal of this task was to determine the BNP or numerical (crisp) relative weights of the five criteria, as outlined in Table 10.

Table 10. The BNP values and their corresponding relative (numerical) weights of all criteria for the land use type I.

Criteria	Si_L	Si_M	Si_U	BNP	Relative Weights	Rank
(C1) CO_2 emission	0.044	0.060	0.087	0.064	0.060	5
(C2) $PM_{2.5}$ concentration	0.178	0.269	0.407	0.285	0.269	2
(C3) CO concentrations	0.092	0.145	0.230	0.156	0.147	4
(C4) Noise levels	0.119	0.186	0.288	0.198	0.186	3
(C5) Pedestrian accident risk	0.222	0.341	0.513	0.359	0.338	1

Note: Si_L, Si_M, and Si_U denote the minimum, most probable, and maximum values of Si, respectively; BNP = Best Non-fuzzy Performance (BNP) value.

Based on the FAHP, the CR values of each expert and the GCR values of the group of 20 experts were estimated, and all of the CR and GCR values were less than 0.1. This indicated that the judgments of each expert and the group of 20 experts were reasonably consistent. As shown in Table 11 and Figure 10, the relative (crisp) weights of each of the five environmental criteria for each land use type according to the group were finally achieved. The number in each bracket is the ranking order of the criterion.

Table 11. Results of fuzzy weights of criteria from all 20 experts derived from the FAHP model.

Main Criteria	Land Use Type I Relative Weights	Rank	Land Use Type II Relative Weights	Rank	Land Use Type III Relative Weights	Rank
(C1) CO_2 emission (CO2E)	0.0600	5	0.0668	5	0.0986	5
(C2) $PM_{2.5}$ concentration (PM2.5C)	0.2685	2	0.2825	2	0.2843	1
(C3) CO concentrations (COC)	0.1467	4	0.1622	4	0.1837	3
(C4) Noise levels (NOL)	0.1864	3	0.1623	3	0.1573	4
(C5) Pedestrian accident risk (PAR)	0.3384	1	0.3261	1	0.2762	2
Total	1.000		1.000		1.000	

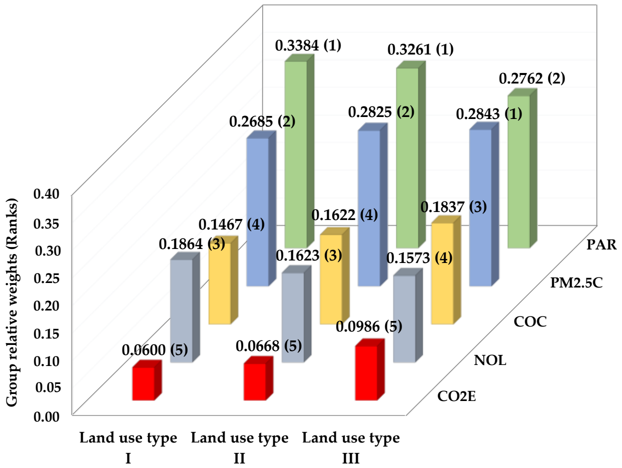


Figure 10. Group relative (crisp) weights of the five criteria for each land use type.

The FAHP was adopted as an effective means of acquiring the practical and professional expertise of experts in terms of the relative importance (weights) of the five environmental criteria for each land use type.

4.3. Quantification of the Performance Scores (TEESs) of All Road Segments for Each Criterion by Using the FSM

The five linguistic (fuzzy) scores—very low (VL), low (L), medium (M), high (H), and very high (VH)—were defined as the five corresponding fuzzy numbers, namely, M_{VL}, M_L, M_M, M_H, and M_{VH}, respectively (as illustrated in Figure 11). Based on the left utility score ($\mu_L(i)$) and right utility score ($\mu_R(i)$) estimated with the FSM [22], the total utility score ($\mu_T(i)$) representing the numerical (crisp) scores of those fuzzy numbers is presented in Table 12.

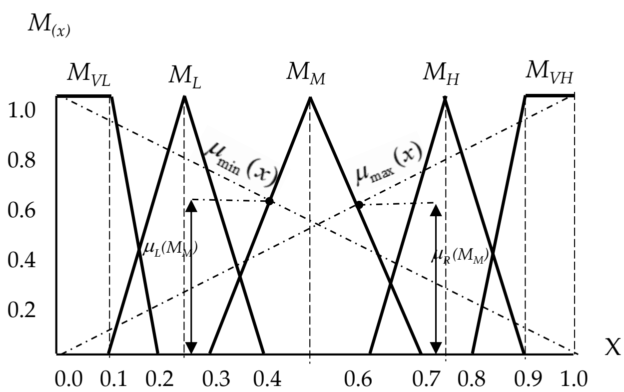


Figure 11. Chen and Hwang's fuzzy scoring method. Adapted from Ref. [22].

Table 12. The total utility scores of the VL, L, M, H, and VH scores. Adapted from Ref. [22].

Performance Scores	TFNs ($M(i)$)	Left Utility Scores ($\mu_L(i)$)	Right Utility Scores ($\mu_R(i)$)	Total Utility Scores ($\mu_T(i)$)	Normalized $\mu_T(i)$
Very low (VL)	M_{VL}	1.0000	0.1818	0.0909	0.1000
Low (L)	M_L	0.7826	0.3478	0.2826	0.3109
Medium (M)	M_M	0.5833	0.5833	0.5000	0.5500
High (H)	M_H	0.3478	0.7826	0.7174	0.7891
Very high (VH)	M_{VH}	0.1818	1.0000	0.9091	1.0000

Given the previously defined fuzzy max ($\mu_{max}(x)$), fuzzy min ($\mu_{min}(x)$), and fuzzy numbers for all performance scores ($M_{VL}, M_L, M_M, M_H, and\ M_{VH}$), as illustrated in Figure 11, the FSM was applied to transform the fuzzy numbers into their corresponding numerical values. For instance, for the fuzzy number M_M, the left utility score ($\mu_L(M_M)$ = 0.5833) could be determined according to the intersection between $\mu_{min}(x)$ and the increasing portion of M_M, and the right utility score ($\mu_R(M_M)$ = 0.5833) could be determined according to the intersection between $\mu_{max}(x)$ and the declining part of M_M, as shown in Figure 11. Based on Equation (16), the total utility score of M_M ($\mu_T(M_M)$) can then be computed as 0.5000. The remaining fuzzy numbers could also be determined by using similar procedures [22]. The FSM was applied to convert the linguistic (fuzzy) scores (e.g., VL, L, M, H, and VH) into the corresponding numerical (crisp) scores for all of the environmental criteria. Notably, the magnitude of each linguistic score for all criteria was identical.

4.4. Prioritization of All Road Segments According to the CTEES Values by Using TOPSIS

All of the CTEES values for each road segment in the study area were estimated by using TOPSIS. The normalized decision values of each decision criterion were calculated by using Equation (18). Then, the weighted normalized matrix was calculated by multiplying the normalized decision matrix by the relative weights of each associated criterion (as presented in Equation (19)). According to the weighted normalized decision matrix, the PIS and NIS were defined by using Equations (20) and (21), respectively. The values of the PIS (V_j^+) and the NIS (V_j^-) for each decision criterion are presented in Table 13.

Table 13. The values of the PIS and the NIS.

All Road Segments	Environmental Criteria				
	CO2E	PM2.5C	COC	NOL	PAR
Positive Ideal Solution (V_j^+)	0.0135	0.0768	0.0664	0.0273	0.0641
Negative Ideal Solution (V_j^-)	0.0012	0.0133	0.0076	0.0131	0.0062

The next step was the calculation of the distance of each road segment from the PIS (S_i^+) and from the NIS (S_i^-) by using Equations (22) and (23), respectively. For example, based on the MMMs, the five performance scores of the top road segment 75 located in land use type I for the CO2E, PM2.5C, COC, NOL, and PAR criteria were "very high (VH)," "medium (M)," "high (H)," "very high (VH)," and "very high (VH)," respectively. An example of calculating the separation values of road segment 75 is illustrated in Table 14.

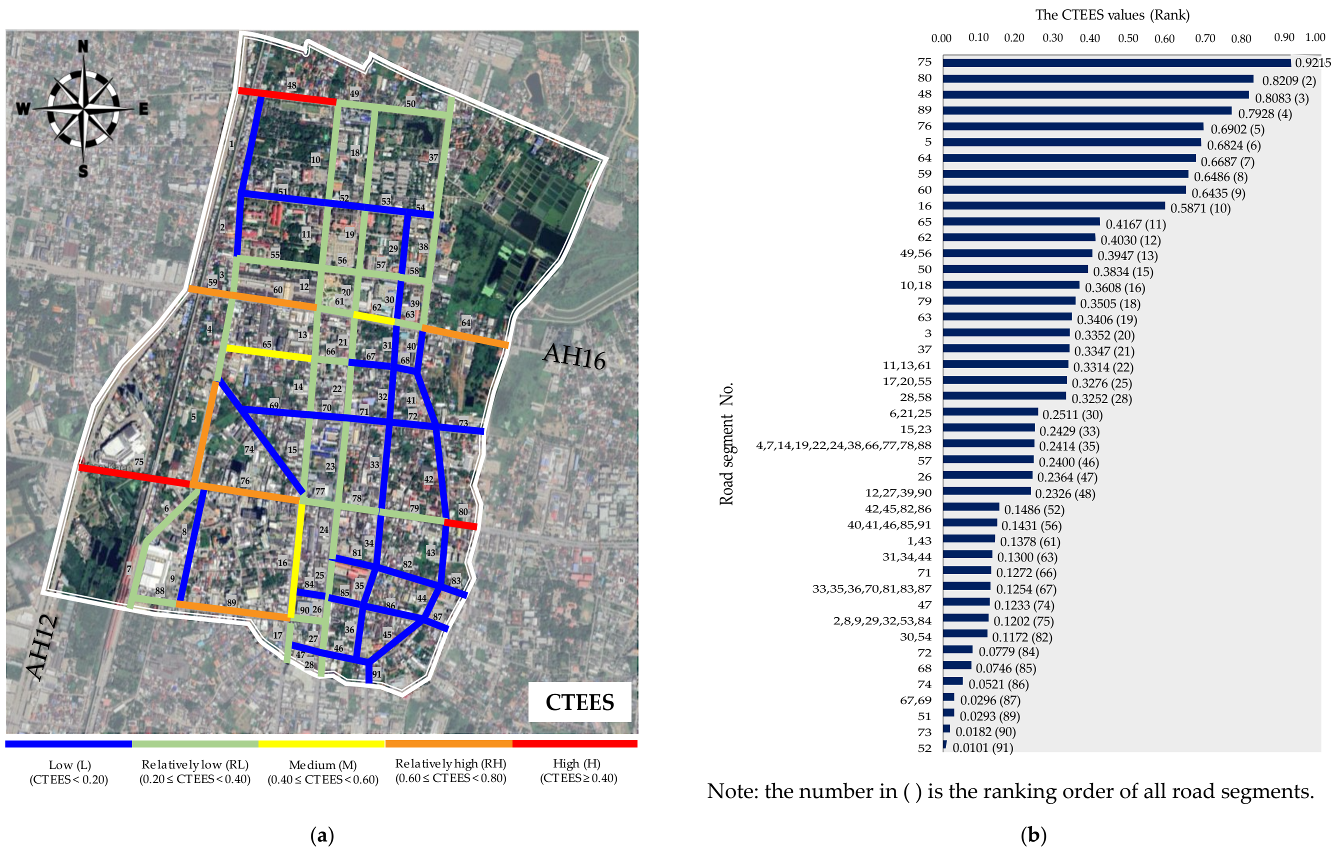
Equation (24) was used to calculate the relative closeness (C_i) of each road segment to the ideal solution. An example of calculating the relative closeness (C_i) to the ideal solution for road segment 75 is presented in the following:

$$C_i = \frac{S_i^-}{S_i^+ + S_i^-} = \frac{0.1038}{0.1038 + 0.0088} = 0.9215 \tag{24}$$

Based on the TOPSIS procedure, as previously mentioned, the estimated CTEES values of all road segments were used to reveal their rankings according to their multicriteria transport-related environmental consequences, as illustrated in Figure 12. The prioritization of the road segments was considered according to the relative closeness (C_i) to the ideal solution in descending order to identify the segments with the most adverse transport-related environmental effects according to multiple criteria [119]. The highest relative closeness (C_i) to the ideal solution for a road segment indicated that that segment faced the worst transport-related environmental effects according to multiple criteria. Hence, the relative closeness (C_i) to the ideal solution (the estimated CTEES value of each road segment) was utilized to rank all of the determined road segments according to the transport-related environmental effects. The magnitudes of the CTEES values were efficiently utilized to identify and prioritize problematic road segments in the urban road network of the study area, as shown in Figure 12.

Table 14. The example of calculating the S_i^+ and S_i^- values of the road segment 75.

Environmental Criteria	Relative Weight (FAHP)	Fuzzy Score (Crisp No.)	Weighted Normalized Values	PIS (V_j^+)	NIS (V_j^-)	$(v_{ij}-V_j^+)^2$	$(v_{ij}-V_j^-)^2$
CO2E	0.0668	1.0000	0.0135	0.0135	0.0012	0.000000	0.000150
PM2.5C	0.2826	0.5500	0.0768	0.0768	0.0133	0.000000	0.004035
COC	0.1622	0.7891	0.0664	0.0664	0.0076	0.000000	0.003460
NOL	0.1623	0.7891	0.0187	0.0273	0.0131	0.000073	0.000032
PAR	0.3261	1.0000	0.0617	0.0641	0.0062	0.000005	0.003087
					Total	0.000078	0.010764
					The separation values	(S_i^+) = 0.0088	(S_i^-) = 0.1038



Note: the number in ( ) is the ranking order of all road segments.

Figure 12. Distribution of the estimated CTEES values and Prioritization of all road segments in the study area. (**a**) Distribution of the estimated CTEES values of all road segments [98]. (**b**) Prioritization of all road segments.

5. Discussion

Based on the five robust MMMs for prediction, the estimated TEESs of all road segments for each environmental criterion were used to evaluate the transport-related environmental effects of each road segment. These TEESs were adopted to identify and rank problematic road segments according to their magnitudes for each criterion, as shown in Figure 8. In addition, the TEESs can be applied to specify the likely causes of transport-related environmental problems of such road segments. For instance, as shown in Figure 8e, segments 48, 49, 56, 62, 75, and 80 had very high (VL) scores, and segments 3, 11, 13, 17, 20, 28, 37, 50, 55, 58, 59, 60, 61, 63, 58, and 79 had high (H) scores for the pedestrian accident risk (PAR) criterion. These road segments can be considered as problematic locations. These road segments urgently require special attention with respect to PAR. A similar interpretation could be applied to the other environmental criteria. In addition, road segment 75 had the following estimated TEESs for the five environmental criteria: (1) a very high (VH) score for the PAR criterion, (2) a very high (VH) score for the NOL criterion, (3) a very high (VH) score for the CO2E criterion, (4) a high (H) score for the COC criterion, and (5) a medium (M) score for the PM2.5C criterion. This indicated that road segment 75 was highly affected by the PAR, NOL, CO2E, and COC criteria. In addition, this road segment was moderately influenced by the PM2.5C criterion. A similar interpretation of these results can be applied to the other road segments. The main factors contributing to problems related to each environmental criterion for each segment can be identified by examining the road's physical and land use characteristics and data on road traffic characteristics. For example, for segment 75, which had a TEES of "very high (VH)" for PAR, the model's input data could be used to analyze the important factors contributing to the PAR criterion. In this instance, the peak hourly traffic volume of 5380 vehicles/h was very high. In addition, the relatively wide effective road width of 12.8 m and the dearth of pedestrian crossings may possibly be the causes of this road segment's problems. A similar interpretation can be applied to other road segments based on other environmental criteria.

As illustrated in Figure 8, the prioritization according to the TEES values of all road segments for each environmental criterion was uniquely distinct. Hence, the determination of the prioritization of the road segments according to the combined transport-related environmental effects of all criteria was complicated. The HMADM technique was, therefore, applied to estimate the composite transport-related environmental effect scores (CTEESs) of the road segments for all criteria. As shown in Table 12 and Figure 10, based on the FAHP, the relative weights of the five environmental criteria typically varied with the land use type. The magnitudes of all relative weights of all criteria achieved for each land use type were relatively compatible, but their ranking orders were quite unique. The prioritization of the relative weights of all criteria for land use types I and II was identical, but it differed from that for land use type III. PAR had the highest relative weight in land use types I and II, followed by PM2.5C, NOL, COC, and CO2E. However, for land use type III, the relative weight of PM2.5C was the highest, followed by those of PAR, COC, NOL, and CO2E. In land use types I and II, the relative weights of PAR were reasonably greater than those of the remaining criteria. In contrast, for land use type III, PM2.5C was the most important criterion. For all land use types, CO2E was the least important environmental criterion. In the proposed HMADM method, when the relative weights of all criteria for each land use type and their corresponding numerical scores for all road segments were quantified, the CTEES values of the road segments estimated with TOPSIS were used to prioritize and assess the transport-related environmental effects. These CTEES values were used to identify and rank problematic locations according to their magnitudes. The estimated CTEESs of all road segments, as shown in Figure 12b, were arbitrarily classified into five equal interval classes as follows: (1) the high (H) class (CTEES $\geq$ 0.8000), (2) relatively high (RH) class (0.6000 $\leq$ CTEES < 0.8000), (3) medium (M) class (0.4000 $\leq$ CTEES < 0.6000), (4) relatively low (RL) class (0.2000 $\leq$ CTEES < 0.4000), and (5) low (L) class (CTEES < 0.2000). Figure 12a illustrates the geographical distribution of all of the estimated CTEESs of the 91 road segments according to the combination of the five environmental criteria. For instance, as shown in Figure 12, the ranking order of the top 12 road segments with the highest CTEES values was 75, 80, 48, 89, 76, 5, 64, 59, 60, 16, 65, and 62, respectively. The top three road segments (segments 75 (CTEES = 0.9215), 80 (0.8209), and 48 (0.8083)) that fell in the high (H) class (CTEES greater than 0.8000) were representative of highly problematic locations. In the relatively high (RH) class (0.6000 ≤ CTEES < 0.8000), road segments 89 (CTEES = 0.7628), 76 (0.6902), 5 (0.6824), 64 (0.6687), 59 (0.6486), and 60 (0.6435) were ranked from the fourth to the ninth in that order. These road segments represented relatively highly problematic locations. From the tenth to the twelfth in the ranking order in the medium (M) class (0.4000 ≤ CTEES < 0.6000) were segments 16 (CTEES = 0.5871), 65 (0.4167), and 62 (0.4030), respectively. These road segments faced moderate transport-related environmental effects according to multiple criteria. Furthermore, the DSM framework was able to specify the possible causes of these problematic locations. For instance, for road segment 75, the ranking order of the key contributing criteria was the following: the PAR criterion (with a "VH" score), the NOL criterion ("VH"), the CO2E criterion ("VH"), the COC criterion ("H"), and the PM2.5C criterion ("M"). A similar interpretation could be applied to the remaining road segments that fell into the other classes (RH, M, RL, and L). In addition, the DSM framework was also able to indicate the proper allocation of limited resources for the implementation of suitable remedial measures for resolving such transport-related environmental problems in the urban road network under study.

During the process of developing the DSM framework, some lessons were learned and some difficulties were noticed: (1) The identification of accurate land use types for each road segment was not simple because the mixture of different land use types in distinct proportions on both sides of the road required careful assumptions and judgments. (2) Two groups of 20 experts (including (i) urban land use and transport planning experts and (ii) environmental experts) were directly interviewed to extract their practical and professional knowledge and expertise in considering the relative weights of all selected environmental criteria for each land use type in the study area. This important process excluded the involvement of a group of stakeholders (actors), such as residents, business owners, visitors, and the public who live or perform their common activities along the considered road segments. The inclusion of the judgments and perceptions of this missing group in the determination of the relative weights would potentially affect the relative weights of all criteria for each land use type and, therefore, the key findings of this research. (3) Because of the different contexts and nature of the underlying transport-related environmental effects in each area, the transferability of the proposed DSM framework to other medium-sized cities in developing countries needs to be examined and tested.

Finally, a similar methodological research framework can possibly be applied to a variety of research areas and practical work, such as in the prioritization and evaluation of suitable policy measures for sustainable urban land use and transport planning, the assessment of the environmental impacts of different sustainable urban public transport development scenarios according to multiple criteria, the prioritization and selection of appropriate locations for constructing transit-oriented development (TOD), and more.

6. Conclusions

In this study, the urban road network of KKMM in Khon Kaen City (KKC), Thailand, was adopted as the study area. Five important transport-related environmental criteria, namely, CO2E, PM2.5C, COC, NOL, and PAR, were determined. An integrated DSM that combined five robust MMMs and a powerful HMADM approach was first introduced to evaluate the transport-related environmental effects of all road segments in the study area according to multiple criteria. These five mathematical models were applied to estimate the CO2E, PM2.5C, COC, NOL, and PAR values for each road segment. Subsequently, in the HMADM approach, a combination of the FAHP, FSM, and TOPSIS was used to determine the CTEES of each road segment. While the FAHP was applied to calculate the relative weights of each criterion for each land use type, the FSM was utilized to transform the linguistic (fuzzy) scores into numerical scores, and TOPSIS was adopted to estimate the CTEESs for each road segment in the study area. The top three road segments (segments 75, 80, and 48) with the greatest CTEESs were representative of the most problematic locations in terms of transport-related environmental problems according to multiple criteria. The magnitude of the TEES values estimated for each environmental criterion of the road segments was subsequently used to identify the key contributing criteria. Based on the collected physical characteristics of the roads, land use characteristics, traffic-related data, and other data, the TEESs were adopted to specify the potential causes of the transport-related environmental problems of the road segments.

According to the overall findings of this research, traffic and transport engineers can apply this DSM framework to specify and prioritize road segments that are problematic in terms of transport-related environmental effects in road segments in urban road networks in medium-sized cities (Khon Kaen City) in developing countries (Thailand). In addition, the DSM can potentially be applied to understand and assess the transport-related environmental consequences of road segments in a study area in terms of both individual criteria and multiple criteria.

This study has several practical implications for managers, administrators, and policymakers. They are as follows:

- The DSM can be efficiently applied in public participation and consultation processes with various groups of stakeholders when an environmental impact assessment (EIA) of any road transport project is conducted.
- The DSM can assist and support less experienced urban transport planners and engineers in comprehending and ranking all determined road segments according to the degree of their transport-related environmental consequences as determined with multiple criteria.
- The DSM can be utilized to allocate limited budgets for the implementation of appropriate remedial measures for mitigating the transport-related environmental consequences of all considered road segments.

In practice, the DSM suffers from several limitations, as discussed below.

- At the current stage, this DSM framework is restricted to the assessment of only five specific transport-related environmental criteria (namely, CO2E, CO, PM2.5C, NOL, and PAR) based on the context of the underlying concerns regarding transport-related environmental impacts. Consequently, this DSM framework cannot be adopted to consider other criteria of transport-related environmental issues. Nevertheless, whenever this DSM is applied in different areas, it is imperative to carefully identify and select the appropriate environmental criteria that hold significance and relevance for each area.
- The DSM can only be applied to quantifiable environmental criteria (from existing prediction models). Therefore, the current DSM cannot be applied to qualitative criteria that are perceived by the public as important transport-related environmental issues.
- Since the NOL [102] and PAR [41] models were originally established in developed countries, the validity of practical applications of such models to KKC, Thailand, was questionable. An assessment of the accuracy of the applicability of such models in medium-sized cities in developing countries is highly recommended.
- Air pollution (including CO2E, CO, and PM2.5C) and noise level (NOL) prediction models may not be perfectly suitable for evaluating the transport-related environmental effects of road segments at a link-based scale because the dispersion of these pollutants among people who live or perform their activities in areas adjacent to such road segments can also be affected. This suggests that the adverse consequences of air and noise pollution should be determined on a larger (area-wide) scale.
- In the DSM framework, the HMADM technique consisted of only the FAHP, FSM, and TOPSIS. This restriction significantly limited the potential applicability and capability of the present DSM framework. However, various potential MADM methods have been developed and tested to improve their potential applicability and advantages and to minimize their weakness and limitations.

- Only two groups of 20 experts ((i) urban land use and transport planning experts and (ii) environmental experts) were directly interviewed to determine the relative weights of all environmental criteria for each land use type. A group of other stakeholders, such as residents, business owners, visitors, and people who live or perform their activities along the considered road segments, was not included in this research.
- The present DSM framework was mainly chosen due to its potential applicability for KKC in Thailand. Since the context of the area and existing transport-related environmental issues in KKC, Thailand, are unique, the transferability of the current DSM framework to any other medium-sized city in a developing country is doubtful.

The following future research directions are recommended.

- Other crucial criteria of transport-related social and environmental effects (both qualitative and quantitative) (e.g., air pollution (e.g., NOx and SOx), difficulty of access, social severance, and road accidents) should be developed, evaluated, and included in future DSM frameworks.
- Several potential MADM techniques (e.g., Complex Proportional Assessment (COPRAS), DEA, and EDAS) should be determined and evaluated for incorporation and testing in the DSM framework in association with fuzzy set theory.
- The inclusion of the group of stakeholders (actors) that was missing here in the determination of the relative weights of all environmental criteria for each land use type is suggested for future research. A comparative analysis of the consequences of the relative weights of all criteria for each land use type according to the different groups of experts and stakeholders is also recommended.
- The transferability of the current DSM framework (primarily focused on KKC in Thailand) to any medium-sized city in any developing country essentially needs to be investigated and evaluated.
- The proposed DSM framework can be integrated with geographical information systems (GISs) and artificial intelligence (AI) technologies to formulate a powerful decision support system in the future.

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