Transport Environmental Effects of Urban Road Network

Subjects: Transportation

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As both developing and developed countries continue to urbanize, rapid urban growth is anticipated, particularly in low- and middle-income countries. 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.

Keywords: sustainability ; environmental impacts evaluation ; MMM

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]. 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 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.

2. 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]				✓									✓		✓	

Several studies [45][46][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].

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
Thomas et al. [44]	✓									✓			✓			
Total	5	2	1	12	10	6	2	3	3	12	1	1	13	2	5	2

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].

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.

3. 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.
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.

Author	Location (Year)	MADM Technique	Study Purpose
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**.

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][86][87][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]

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