

Article

Classification of Roadway Context and Target Speed for Multilane Highways in Thailand Using Fuzzy Expert System

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Abstract: The classification of roadway contexts and speeds is a critical step in the planning, design, and operation of highway infrastructure. In developing countries, road users encounter safety and operational issues due to poorly defined roadway contexts and inappropriately determined target speeds for a highway network. This study developed an expert system for classifying roadway contexts and target speeds of multilane highway segments and applied the classification process to 16,235 km of multilane highways in Thailand's highway network. The proposed methodology used a fuzzy decision mechanism to deal with subjective and imprecise expert judgment (e.g., low, high), many variables, and a complex evaluation process. This study used the Fuzzy Delphi method to identify the possible important factors influencing contexts and speeds and the Fuzzy Inference System method to reason factors to categorize multilane highway segments in Thailand into different classes of roadway contexts (e.g., rural, low-density suburban, high-density suburban, and urban highways) and target speeds (e.g., ≤ 50 km/h, 50–60 km/h, 60–70 km/h, 70–80 km/h, 80–90 km/h, 90–100 km/h, and 100 km/h). The study was based on data from questionnaire surveys of experts and field investigations of 120 highway segments. The results showed that roadside environments and activities influence the roadway contexts, while the target speeds are sensitive to the roadway characteristics and contexts. These findings support the need for changes in context-adapted highway design and speed management. The proposed expert system provided high accuracy (90.8%) in classifications of both roadway contexts and target speeds. The fuzzy expert system provides a systematic and structural framework for analyzing imprecise data in highway contextual and speed classifications and improving the clarity and accuracy of the evaluation process. The implementation of the fuzzy expert system has the potential to revolutionize the highway classification decision-making problem under uncertainty.

Keywords: sustainable safety; highway classification; roadway context; target speed; fuzzy expert system; decision making



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1. Introduction

In a sustainable road traffic safety system, the classification of roadway contexts and speeds for highways has been recognized as one of the essential design principles for preventing deaths and serious injuries. It is a critical prerequisite for the planning of highway infrastructure networks and the design and operation of highway facilities. According to the sustainable safety vision, a highway network must be hierarchically classified; its safe speed class must be appropriately applied; and its design must align with road user competencies [1].

In Thailand's highway network, road users encounter safety and operational issues due to the lack of a clear hierarchy in highway design and its disconnection from land

use integration. This results in a poorly ordered road hierarchy, a poorly defined roadway context, and inappropriately determined target speeds. The consideration of context and speed classification has recently gained attention to safely and efficiently serve the intended functions of highways and the expectations of road users. Many authorities emphasize the need for logical and accurate highway and speed classifications, and they place a strong emphasis on designing roads to fit the context and speed of the site. [2]

Classification of roadway contexts for highways is the process of differentiating highway segments based on environmental contexts. It is an updated concept of highway classification. Traditionally, highways are classified according to their dual functions of mobility and accessibility into different types, such as freeways, arterials, collectors, and local roads [3,4]. This highway functional classification system is, however, affected by land use and urban layout. Highway functions may not perform as intended due to the changes in land use [5]. Furthermore, researchers have considered not only road functions but also expected future contextual conditions in highway classification [6]. This highway contextual classification determines context categories to which a given highway belongs based on the expectation of road users to maneuver along an area, such as urban, suburban, and rural highways [7,8]. Classification of roadway contexts allows for a more precise classification and helps the designer devise appropriate context-sensitive highway design solutions.

Classification of speeds for highways is the process of designating the appropriate target speed for given highway segments according to geometric characteristics and roadside environments. The target speed is the highest speed at which vehicles should operate on a roadway in a specific context and given roadside multimodal activities. It is the speed that the designer intends for drivers to use [3,9,10]. In sustainable safety, the identification of appropriate target speeds for roadway designs is of importance. Speed limits and operating speeds should be matched with target speeds to minimize the risk of road users being involved and severely injured in a crash [11]. Previous studies on speed management presented several approaches and used different factors for speed settlement [8]. The classification of highway speeds has changed recently to take into account the context and the surrounding environment. It also allows for the safer design of the road and roadside [9,11].

In this study, the classification of roadway contexts and speeds for highways is considered as decision making under uncertainty to deal with a complex evaluation process, subjective and imprecise judgment, and many variables. This study focuses on classifying the roadway contexts and target speeds of multilane highway segments in Thailand's highway network. The contexts of the roadway are classified based on context development into five categories, including rural (R), low-density suburban (SL), high-density suburban (SH), urban (U), and urban core (UC) highways. The target speeds are classified into seven categories, including ≤ 50 km/h, 50–60 km/h, 60–70 km/h, 70–80 km/h, 80–90 km/h, 90–100 km/h, and ≥ 100 km/h.

According to the Thailand Department of Highways database, there are 16,235 km of multilane highways, which account for 30.8% of all highways. Most multilane highways in Thailand are principal or minor arterials with at least two lanes in each direction with no or partial control of access. They typically serve two cities or major activity centers that account for a high number of traffic volumes. Figure 1 illustrates different views of multilane highway segments in Thailand's highway network.

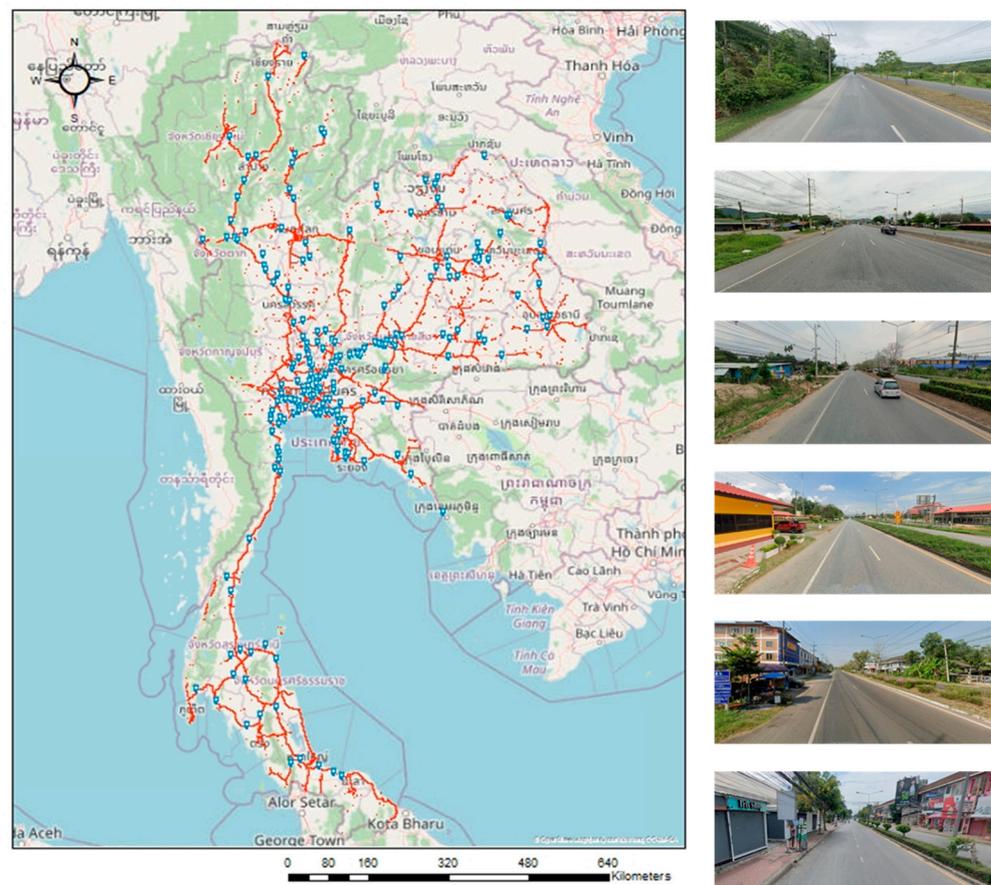


Figure 1. Examples of multilane highway segments in a highway network in Thailand.

This study proposes an expert system for evaluating roadway contexts and target speeds of multilane highway segments in a highway network in Thailand. The proposed methodology uses a fuzzy decision mechanism to preserve language-based expert opinions throughout the evaluation process. This study applies the Fuzzy Delphi method to identify the possible important factors affecting the contexts and speeds of multilane highways and then applies the Fuzzy Inference System method to the classification of contexts and target speeds of multilane highway segments, such as urban 60 km/h, suburban 70 km/h, rural 80 km/h, or rural 90 km/h.

The remainder of this paper unfolds in different sections. Section 2 reviews past studies related to roadway classification and target speed setting and concepts related to a fuzzy expert system. Section 3 illustrates the methodology used. Section 4 describes the results and offers a discussion of the results. Section 5 concludes the study findings and highlights further recommendations.

2. Literature Reviews

The reviews of the literature are categorized into three parts. Section 2.1 presents the concept of highway classification. Section 2.2 reviews the settlement of target speeds. Section 2.3 explores the decision mechanisms under a fuzzy environment.

2.1. Highway Classification

A highway classification system plays a significant role at the early stage of the highway development process to determine its roles and design standards. A functional classification system, also known as the classification of road types, is a classical highway classification that systematically designates the role of the roads in a highway network into the orderly class according to the dual functions of roads: mobility function and accessi-

bility function [3,4,8,12,13]. Mobility is concerned with the efficiency of traffic, whereas accessibility is concerned with the convenience of entry and exit. Highway functional classification has been implemented by various countries in the highway planning and design process to organize road networks hierarchically. In the conventional practice of highway engineering, the functionality of roads is categorized into four main classes: freeways, arterials, collectors, and local streets.

This functional classification, however, inadequately accounts for the interaction of land use development patterns. The classification of highways was therefore reevaluated. It further took into consideration the development of contexts due to the distinction of traffic characteristics, user needs, and the constraints of the surrounding environments. Jones et al. introduced the concept of 'Link and Place' for roadways in an urban context based on their 'Link' and 'Place' functions [14,15]. 'Link' represents the through movement of users seeking to minimize travel time, while 'Place' represents the destination locations of users seeking to spend time there. This concept accommodates the needs of people (all road users) rather than vehicles only. AASHTO's *Highway Safety Manual* evaluated highway performances differently based on their locations and contexts in urban, suburban, and rural areas [16]. Nevertheless, there were no clear quantitative criteria for classification, and decisions were made based on the discretion of the analysts.

In recent years, the expanded functional classification system that combines context categories into the conventional highway classification system was suggested in the *NCHRP Report 855* [6]. This context-based classification of a highway characterizes roadways based on their current and anticipated future contexts and user needs. This report proposed five basic context categories, ranging from very little to very high development.

- The rural context is characterized by the lowest density, with few structures and large structure setbacks.
- The rural town context is characterized by low to medium density with concentrated development, including on-street parking and sidewalks with small setbacks.
- The suburban context is characterized by medium density, with mixed-use clusters. There are varied setbacks, with some sidewalks and mostly off-street parking.
- The urban context is characterized by a high density of mixed-use functionality. There are sidewalks with small on-street parking and closely spaced setbacks.
- The urban core context is characterized by the highest density, with high-rise structures. There are sidewalks and restricted on-street parking.

More recently, a variety of context categories and subcategories have been introduced. The Florida Department of Transportation (FDOT) *Context Classification Guide* developed eight contexts, including a natural context, a rural context, a rural town context, two suburban contexts (suburban residential and suburban commercial), two urban contexts (urban general and urban center), and an urban core context [17]. The contextual classification studies are further categorized into nine contexts, including natural, rural, rural crossroad, suburban residential, industrial–warehouse–port, suburban commercial, urban residential, urban commercial, and urban core [18].

The measures used in the context-based classification are diverse, such as land use, building and structure density, building size and scale, building placement or orientation, building setback, parking presence and location, intersection density, block perimeter, block length, frontage types, traffic volume and mix, pedestrian patterns, bicyclist patterns, vulnerable road user patterns, transit, crash data, population density, employment density, residential density, office/retail density, and short trip opportunity area. The descriptions of these measures can be further reviewed in the literature [7,14,15,17–20]. However, there are no general qualitative measures used for each context. The contextual classification gives planners flexibility to determine the class of highways, and it helps designers develop context-adapted designs to meet the expectations of all road users.

2.2. Target Speed Determination

Speed is one of the main parameters that characterizes highway safety and operations. Design speed is the common term used by transportation professionals to establish the design values of highway geometric elements, such as stopping sight distance, the curvature and superelevation of horizontal curves, etc. Ideally, the selected design speed should be the same as the maximum safe speed of motorists, influenced by the speed limits and the design features of the highway [3].

Target speed is another term also used by transportation professionals to describe the speed at which a designer intends motorists to travel on a roadway in a specific context [20]. Numerous practices have recommended substituting target speed for design speed, particularly for urban areas where the safe speed is lower than the design speed. The concept of target speeds has recently been considered in relation to context-sensitive roadway design and speed management [9,10]. For a given roadway, appropriate target speeds should be determined for the safe design of the roadway and the environment for all road users. The target speed is sometimes meant to serve as the context-appropriate speed limit [21].

There are two concepts at play in identifying target speeds for a given road section [10,11,22]. First, the harm minimization concept, called the 'Safe System' approach, considers the crash types that are likely to occur for different road types and the tolerance of the human body to impact forces. The target speed is set based on the safe speeds corresponding to a 10 percent chance of a fatal injury by crash types (e.g., pedestrian and motorcycle crash 30 km/h, angle crash 50 km/h, head-on crash 70 km/h) [23]. This approach results in low but safe speeds for all road users.

Second, the context-adaptive speed concept recommends setting the target speeds to the highest speed at which motorists should operate based on the roadway context, multimodal traffic generated by adjacent development, and potential risks to vulnerable road users. *NCHRP Report 855* suggested target speeds by roadway context and type. For instance, for arterials, the suggested target speed is 80 km/h or higher for a rural context, 50 km/h or lower for a rural town context, 70 km/h or lower for a suburban context, 50 km/h or lower for an urban context, and 40 km/h or lower for an urban core context [6]. This approach hypothesizes that the target speeds are highly sensitive to the roadway context and may require incremental changes to roadway design, speed management, and speed enforcement [17,24].

In practice, there has been no consensus relating to the methods for determining the target speed and appropriate speed limit for a given road section. A number of highway engineering studies proposed an expert system approach that involves the knowledge and inference of experts to advise speed selection. These expert systems use a decision algorithm and a set of rules to advise the speed selection for particular situations. The systems rely on specific factors that influence the target speeds, including lane width, shoulder width, median width, road width, number of lanes, surrounding development, access density, intersection density, the presence of roundabouts, road function, section length, setback, roadway context, population density, roadside hazards, traffic volume, the mix of vehicles and modes, pedestrian patterns, cyclist patterns, vulnerable road user patterns, transit services, pavement condition, alignment, crash history, transition zones, parking, and special conditions [25–29]. Factors affecting the speeds are diverse in the existing literature, and many of them are subjective and uncertain. The selection of the most reasonable impact factors and methods to identify the appropriate target speeds in a given highway segment is thus an essential step in highway planning and design.

2.3. Decision Making under Fuzzy Environments

2.3.1. Fuzzy Delphi Method for Screening Criteria

The Delphi method, first proposed by Dalkey and Helmer in 1960, is a structured and iterative multistage process for building consensus from individual opinions on a specific topic. It employs a series of questionnaires in two or more rounds, including

gathering insights and feedback from a panel of experts and adjusting ratings to arrive at group opinions or decisions [30]. This method is widely used to generate forecasts and develop screening and prioritizing items. It is based on the views of experts using verbal expressions and sometimes quantifying by rating scales.

However, this traditional Delphi method has some limitations. The quantification of expert opinions may not fully reflect their thinking nature. Verbal expressions may not have a clear and well-defined meaning in real-world decision-making problems. When individual experts are judging, an event may significantly differ because each of them has a different subjective perception. In addition, the crisp rating scales may not accommodate the inherent subjectivity in expert opinions.

The Fuzzy Delphi method combines the Delphi method with the fuzzy set theory to address the ambiguity of the panel consensus during the decision-making process. This method is an extension of the Delphi method. This method uses fuzzy numbers to quantify expert opinions and fuzzy statistical analysis to test the consensus in each round of the questionnaire. The review process is repeated until convergence [31,32].

The Fuzzy Delphi method has several advantages over the traditional Delphi method. First, expert opinions can be expressed more completely and consistently by applying fuzzy numbers to appropriately express linguistic descriptions and accurately reflect subjective judgments. Second, expert knowledge can be made more rational and meet the requirement through the fuzzy set theory introduced by Zadeh in 1965 [33–37]. Finally, expert survey time and cost can be reduced due to the reduction in error level and the fewer number of surveys [38,39]. Since its introduction, numerous studies have been conducted using the Fuzzy Delphi technique, such as for screening criteria [40].

This method is based on an iterative approach, which involves two or three rounds of expert interviews. In the first round, all experts are asked to assign the fuzzy importance value of all factors, and the opinions are gathered and verified. If no consensus exists, then they are asked to revise their evaluation until the opinions converge. In this method, the ‘double-triangle fuzzy numbers’ operation is used to aggregate experts’ opinions, and the ‘grey zone’ test is used to examine whether experts’ opinions are consistently converged [39].

2.3.2. Fuzzy Inference System for Classification and Reasoning

A Fuzzy Inference System (FIS), sometimes called a fuzzy-rule-based system, a fuzzy expert system, a fuzzy logic controller, a fuzzy modeling, or a fuzzy system, is an inference mechanism for formulating the mapping from a given input to an output using a set of rules. The input and/or rules are fuzzy, and thus the output becomes fuzzy.

Fuzzy Inference Systems (FISs) typically consist of four main components: the fuzzifier, the inference engine, the knowledge base, and the defuzzifier. A fuzzifier process transforms numerical values into fuzzy sets, and the membership degree of each linguistic variable is obtained. A knowledge base contains a collection of if–then fuzzy rules that represent experts’ linguistic reasoning. An inference engine uses the if–then rules in a knowledge base to map inputs and outputs. It applies the fuzzy rule base to the fuzzy sets to obtain a fuzzy outcome. A defuzzifier process transposes inferred knowledge into a rule action or a single value output [41–43].

In classification and reasoning under uncertainty, an outcome is computed based on the degrees of truth (degrees of membership) between 1 and 0 rather than a binary outcome (true or false: 1 or 0). In classification problems where no clear classification exists and degrees of uncertainty are involved, FIS allows for the consideration of intermediate values in the categories. These categories are expressed as linguistic variables (e.g., low, medium, high). In reasoning where decisions are made based on imprecise knowledge and non-numerical information, FIS allows for modeling and evaluating complex scenarios using a set of rules and linguistic variables (e.g., if one independent variable is low, then the outcome is high) [33].

Given the input variables of x_1 , x_2 , and x_3 to draw a conclusion of z , the mechanism of fuzzy inference is as follows:

Input: x_1 is A^* and x_2 is B^* , and x_3 is C^* .
 Rule 1: If (x_1 is A_1) and (x_2 is B_1) and (x_3 is C_1), then z is D_1 .
 Rule 2: If (x_1 is A_2) and (x_2 is B_2) and (x_3 is C_2), then z is D_2 .

 Conclusion: z is D^* .

The inputs A^* , B^* , and C^* derived from data collection may be exact or appropriate values. The premises in the rules (A_i , B_i , C_i) derived from expert knowledge may also be approximate, such as *Low*, *High*. The conclusion D^* , which is the consequence of the fuzzy inference, may be approximate.

To draw a conclusion, first, the degree to which the inputs (A^* , B^* , C^*) satisfy the premises (A_i , B_i , C_i) for each rule is calculated by the fuzzy set operation. Next, the implication operator is used to determine the fuzzy set that represents the conclusion of the rule. The aggregation operator is then applied to aggregate the conclusion of each rule into a single fuzzy set. Finally, the output fuzzy set is quantified using the defuzzifying operation, normally using the center of gravity method to obtain the final output [44].

Over past decades, FISs have been applied to numerous real-world problems, such as decision analysis, expert systems, data classification, project management, automatic control, and computer vision, in various disciplines, such as engineering, medicine, chemistry, computer networks, pattern recognition, finance, and business [45–48]. The main advantage of FIS is the ability to handle decision-making problems with unclear classification, imprecise information, or subjective human feelings and expertise.

3. Materials and Methods

The research methodology adopted in this study consisted of four major phases, as illustrated in Figure 2. The main focus was to develop an expert system for classifying roadway contexts and target speeds of multilane highway segments in Thailand. The study first defined the possible important factors affecting roadway contexts and target speeds, and the most influential factors were considered as inputs of the system. Then, all relevant data related to the input variables were collected. Furthermore, the expert survey was used to develop expert knowledge and rules. Finally, the expert system for classifying road contexts and target speed was evaluated.

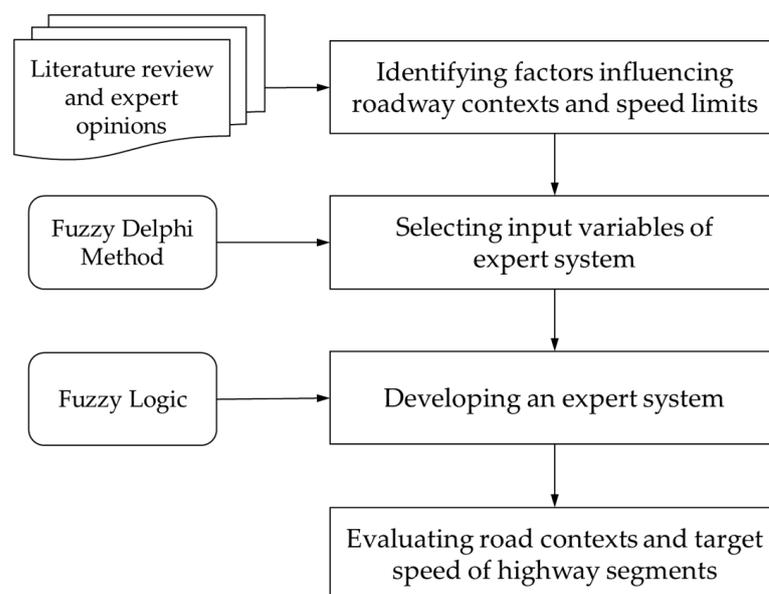


Figure 2. The research method adopted in this paper.

3.1. Data

The study was based on data from 446 highway segments over 16,235 km of multilane highways across the nation, as presented in Figure 1. The selected multilane highway segments were at least 3 km in length, with homogeneous cross-sections and relatively constant speed along a roadway. In this study, a total of 120 samples were investigated. These samples were representative of various roadway and environmental characteristics of multilane highway segments in Thailand.

Relevant data were obtained from both field data collection and questionnaire surveys. First, the study gathered data related to each of the explanatory variables through direct observation in situ and examination from the Highway Traffic Information System database. The investigation was conducted from May to October 2023.

Second, the study conducted questionnaire surveys to elicit expert opinions related to context and speed classifications. For each highway segment, a video of a 1 km homogeneous road stretch was recorded and presented to the experts. Each expert was asked to provide their perceptions related to the selected input variables and to conduct the contextual and speed classification of 30 samples of multilane highway segments. The experts attributed linguistic variables to input variables and classified the roadway context and target speed of the highway segments.

A panel of 12 experts was selected for inclusion in a questionnaire survey. This study used a purposive sampling technique to select a specific group of individuals based on their experience and expertise in the field of highway and traffic safety engineering. They consisted of 6 engineering professionals and 6 academic scholars. It is noted that a minimum sample of experts of 10 is recommended in fuzzy decision-making studies to obtain high uniformity among experts [49,50].

3.2. Selection of Contributing Factors

This study established a set of potential factors influencing roadway contexts and target speeds for multilane highways based on an extensive literature review, expert interviews, and focus group discussion [17–28,51–54]. All relevant factors and their descriptions were presented individually to experts for their feedback, and experts interacted with the questionnaire by adding, removing, and revising the factors in the list, if necessary. Each factor was tested for validity in terms of the clarity of meaning.

A total of 13 factors affecting roadway contexts and 17 factors affecting target speeds of multilane highway segments in Thailand were delimited. They were grouped into two metrics: roadway and traffic-related elements and non-roadway elements. It is noted that roadway and non-roadway factors can affect context classification, speed classification, or both classifications.

This study adopted the Fuzzy Delphi method to select the factors affecting roadway contexts and target speeds. The Fuzzy Delphi method includes the following steps:

- Step 1: Collecting opinions from the decision group. Each expert k was asked to give an interval importance value on a scale ranging from 1 to 10 based on its importance for each impact factor i , $S_i = (C_i^{(k)}, O_i^{(k)})$; $i = 1, 2, \dots, n$. For the quantitative score of the factor, the minimum of the interval value $C_i^{(k)}$ represents the expert's 'conservatively perceived value (C)', and the maximum of the interval value $O_i^{(k)}$ represents the expert's 'optimistically perceived value (O)'.
- Step 2: Aggregating the opinions of all of the experts. The interval values associated with each factor i given by all experts were combined by calculating the lower bound, the mean value, and the upper bound of the conservatively perceived value $C_i = (C_i^L, C_i^M, C_i^U)$ and the optimistically perceived value $O_i = (O_i^L, O_i^M, O_i^U)$. These two triangular fuzzy numbers, called the double-triangle fuzzy numbers, were obtained.
- Step 3: Determining the experts' consensus. Given the double-triangle fuzzy numbers, the overlap between these two, called the grey area Z_i , was examined. Three alterna-

tives, as shown in Figure 3, could be found, and the aggregated opinions associated with each factor i (G_i) were calculated.

- If there is no overlapping section $C_i^U \leq O_i^L$, then experts' opinions of factor i are converged. The aggregated importance value G_i is the arithmetic mean of C_i^M and O_i^M ; $G_i = (C_i^M + O_i^M) / 2$.
 - If there is an overlapping section $C_i^U > O_i^L$, and $Z_i \leq M_i$, then experts' opinions of factor i are compromised. The aggregated importance value G_i is the most satisfying of the overlapping sections; $G_i = \max\min\{C_i, O_i\}$.
 - If there is an overlapping section $C_i^U > O_i^L$, and $Z_i > M_i$, then experts' opinions of factor i are divergent. Steps 1 to 3 are repeated until all opinions are converged and the aggregated importance value is obtained.
- Step 4: Screening important factors. The most critical factors were established based on the threshold of an important value. The threshold value of 8.0 is selected in screening criteria, but it varies based on the researcher's interest in different studies. If the importance value of aggregated experts' opinions is larger than the threshold, then the factor is accepted; if not, it is excluded.

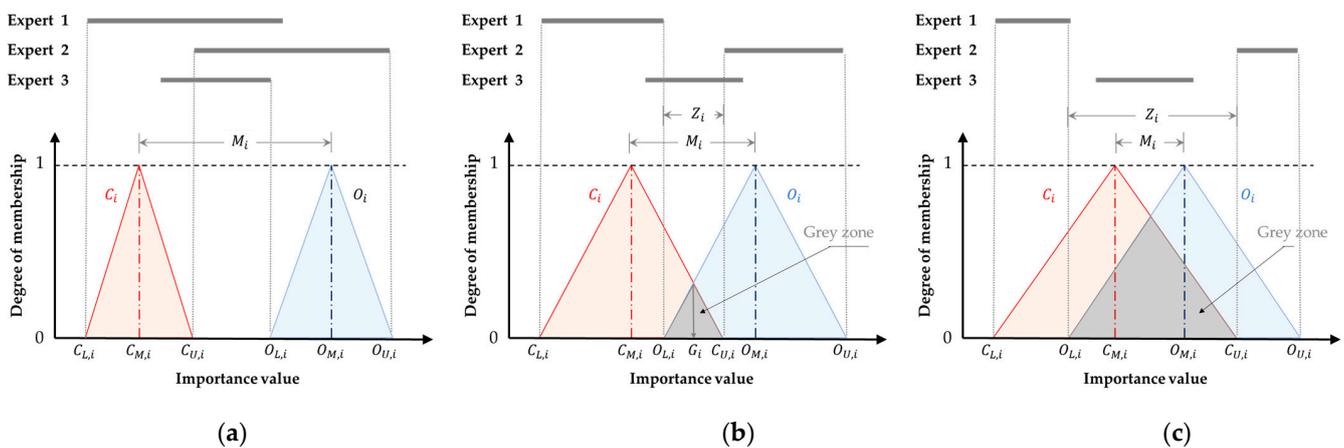


Figure 3. Double-triangular fuzzy numbers: (a) converge; (b) compromise; (c) divergent.

The lists of potential factors and their description and importance values (G values) are presented in Table 1 for roadway contexts and in Table 2 for target speeds. Based on expert surveys, many factors affected either roadway contexts or target speeds or both. Although other factors significantly affect the context and speed classifications, this study selected the highest critical factors to develop the expert system. The importance values indicated that the most critical factors (*) influencing roadway contexts were building density, building setback, and parking activity, while those influencing target speeds were context development, lateral clearance, access density, and traffic modal mix.

Table 1. List of factors affecting roadway context classification.

Category	Factor	Description	G
Roadway and traffic-related elements	Right-of-way	The width of road right-of-way designated for use as a highway under the Highways Act, including the travel ways, shoulders, sidewalks, utilities, drainage facilities, and any other roadway facilities	8.15
	Intersection density	The number of at-grade intersections per distance	8.34

Table 1. *Cont.*

Category	Factor	Description	G
Roadway and traffic-related elements	Access density	The number of access points per distance	8.87
	Parking activity	The presence of on-street parking activity alongside roadways	9.33 *
	Traffic flow	The amount of traffic volume along roadways	8.25
	Motorcycle activity	The amount of motorcycles that use access to or travel along roadways	8.67
	Pedestrian activity	The amount of pedestrians who use access to roadways	8.55
Non-roadway elements	Land use	The qualitative description of fronting properties, e.g., residential, commercial, industrial, or agricultural	8.58
	Building density	Existence of build-up area (building/structure) as a percentage of the land area along roadways	9.67 *
	Building setback	The distance from buildings to adjacent roadways	9.50 *
	Building height	The height of buildings on the fronting properties	8.63
	Population density	The population per area as a surrogate for transportation activity	8.17
	Employment density	The number of jobs per area adjacent to either side of the roadway as a surrogate for commuting activity	8.05

Note: The threshold value of 8.0 was applied to the screening criteria.

Table 2. List of factors affecting roadway target speed classification.

Category	Factor	Description	G
Roadway and traffic-related elements	Pavement width	The width of paved travel way on roadways	8.96
	Shoulder width	The presence and width of shoulders, including both left and right shoulders in the same direction	9.09
	Median type and width	The type and width of the median (e.g., raised median, depressed median, curb median, concrete median barriers)	8.45
	Lateral clearance	The distance between the edge of the carriageway to the nearest fixed object or support	9.20 *
	Access density	The number of access points or at-grade U-turns per distance	9.56 *
	Segment length	The length of road sections	8.05
	Horizontal curvature	The curvature of road alignment (number of curves, curve radius)	8.67
	Vertical alignment	The grade of roadway alignment	8.75
	Parking presence	The presence of on-street parking activity alongside roadways	8.51
	Sidewalk presence	The presence of sidewalks along roadways	8.30
	Traffic flow	The traffic volume along roadways	8.07
	Traffic modal mix	The proportion of mixed traffic or non-passenger cars in a traffic stream	9.17 *
Pedestrian activity	The amount of pedestrians who use access to roadways	8.40	

Table 2. Cont.

Category	Factor	Description	G
Non-roadway elements	Land use	The qualitative description of fronting properties, e.g., residential, commercial, industrial, or agricultural	8.15
	Context development	The type and pattern of context/development along roadways	9.40 *
	Roadside density	The density of roadside objects (e.g., utility poles, light supports, trees, bridge abutments)	8.70
	Plant intensity	The type and intensity of plants along roadways (e.g., grass, low plants, light shrubs, heavy shrubs, heavy trees)	8.10

Note: The threshold value of 8.0 was applied to the screening criteria.

3.3. Development of Fuzzy Expert System

This study adopted the Fuzzy Inference System (FIS) as an expert system for the classification of roadway context and target speed for multilane highways. The study used the fuzzy toolbox in MATLAB to design a fuzzy expert system with Mamdani logic. The proposed expert system consists of two sequential inference systems. The framework of the proposed expert system is presented in Figure 4.

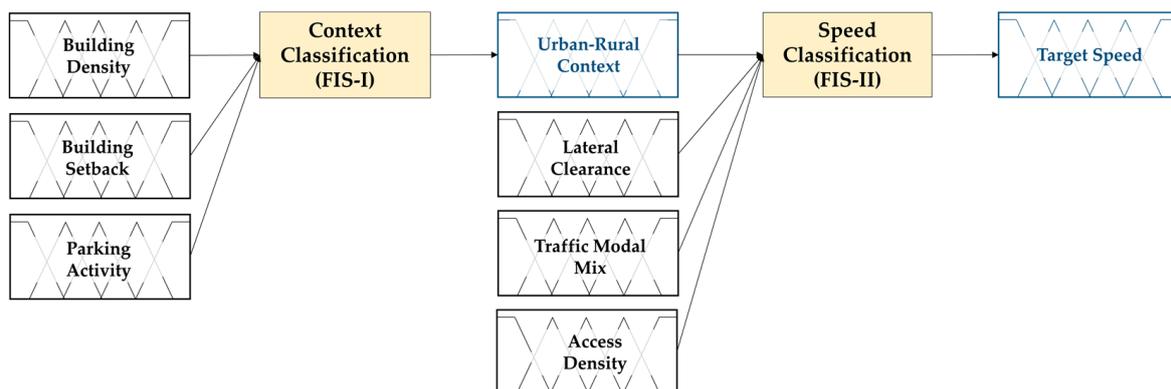


Figure 4. The framework of Fuzzy Inference Systems.

The first system (FIS-I) determines the roadway context of each highway segment, and the second system (FIS-II) identifies its target speed. There are six variables as the inputs and two variables as the outputs of the Fuzzy Inference Systems for context and speed classification of highways. The expert system classifies multilane highway segments in Thailand into five classes of roadway contexts (rural (R), low-density suburban (SL), high-density suburban (SH), urban (U), and urban core (UC)) and seven classes of target speeds (≤ 50 km/h, 50–60 km/h, 60–70 km/h, 70–80 km/h, 80–90 km/h, 90–100 km/h, and ≥ 100 km/h). The development of a fuzzy expert system involves input variables, membership functions, and fuzzy rules described in the following subsections.

3.3.1. Input Variables

Six input variables were selected from the previous section, including building density, building setback, parking activity, lateral clearance, traffic modal mix, and access density. The first three attributes were used in the context classification (FIS-I), while the last three attributes together with the roadway contexts derived from FIS-I were used in the speed classification (FIS-II).

Based on field investigation and highway databases, this study gathered data related to six input variables of 120 multilane highway segments across the highway network.

Table 3 presents the input variables, their descriptions, the linguistic variables, and the application intervals from the selected highway segments.

Table 3. Summary of input variables, descriptions, and linguistic variables.

Input Variable	Description	Linguistic Variables	Min	Max	Average
Building density	The percentage of build-up area on the fronting parcels to the land area along roadways	Very low, low, medium, high, and very high	10	82	55.0
Building setback	The distance of structures to the roadway	Small, medium, and large	1.0	4.8	3.5
Parking activity	The percentage of the roadway with on-street parking being occupied	Very low, low, medium, high, and very high	5	65	23.5
Lateral clearance	Lateral distance from the edge of the travel way to a roadside feature	Small, medium, and large	1.5	4.5	3.1
Traffic modal mix	The percentage of motorcycles and heavy vehicles	Very low, low, medium, high, and very high	7	27	15.6
Access density	The number of access points per distance	Low, medium, and high	2	10	6.8

3.3.2. Membership Functions

In fuzzy set theory, a fuzzy set A in X is characterized by a membership function (or the degree of truth) $m_A(x)$ in the range $[0, 1]$, $m_A(x) : X \rightarrow [0, 1]$. If $m_A(x) = 1$, x is completely compatible with A (i.e., true). Similarly, if $m_A(x) = 0$, x is completely incompatible with A (i.e., not true).

The membership functions to individual input and output attributes were constructed based on data collection and questionnaire surveys. For each attribute, the values are treated as fuzzy sets in the form of membership functions. The membership functions represent the degree (between 0 and 1) to which the values belong to each of the respective fuzzy sets. Various membership functions can be considered to represent belonging to each linguistic variable, including triangular, trapezoidal, gaussian, and sigmoidal.

The inputs are fuzzified using triangular and trapezoidal membership functions due to their simplicity and ease of implementation in a computer program. They are the most common functions to model Fuzzy Inference Systems. The triangular and trapezoidal functions are used for the linguistic variables in the middle and on the borders, respectively. The membership functions follow three conditions: they are normalized, they are convex, and their supporting set is bounded and piecewise continuous.

The membership function is displayed with three real numbers, $F = (m_1, m_2, m_3)$, where m_1 , m_2 , and m_3 are the minimum, most probable, and maximum values of fuzzy number, respectively. Fuzzy numbers can be formed based on partial information about the smallest and largest possible values and the most probable uncertain values, and their membership function is written in Equation (1).

$$m(x) = \begin{cases} \frac{x-m_1}{m_2-m_1}; & m_1 < x \leq m_2 \\ \frac{m_3-x}{m_3-m_2}; & m_2 < x \leq m_3 \\ 0; & \text{otherwise} \end{cases} \quad (1)$$

There are six variables as the inputs of the Fuzzy Inference System, including building density, building setback, parking activity, lateral clearance, traffic modal mix, and access density. The set and interval of input variables are justified by experts based on available data. The sets of membership functions for input variables are shown in Figure 5. Furthermore, there are two variables as the outputs of the Fuzzy Inference Systems, including roadway contexts and target speeds. The set and interval of roadway contexts and target

speeds are set in accordance with the predefined categories. In this study, the contexts of roadways are classified into five categories, including rural (R), low-density suburban (SL), high-density suburban (SH), urban (U), and urban core (UC) highways, and the target speeds are classified into seven categories, including ≤ 50 km/h, 50–60 km/h, 60–70 km/h, 70–80 km/h, 80–90 km/h, 90–100 km/h, and ≥ 100 km/h. The sets of membership functions for output variables are also shown in Figure 5. It is noted that the membership functions can be any shape, interval, and number for applications under consideration.

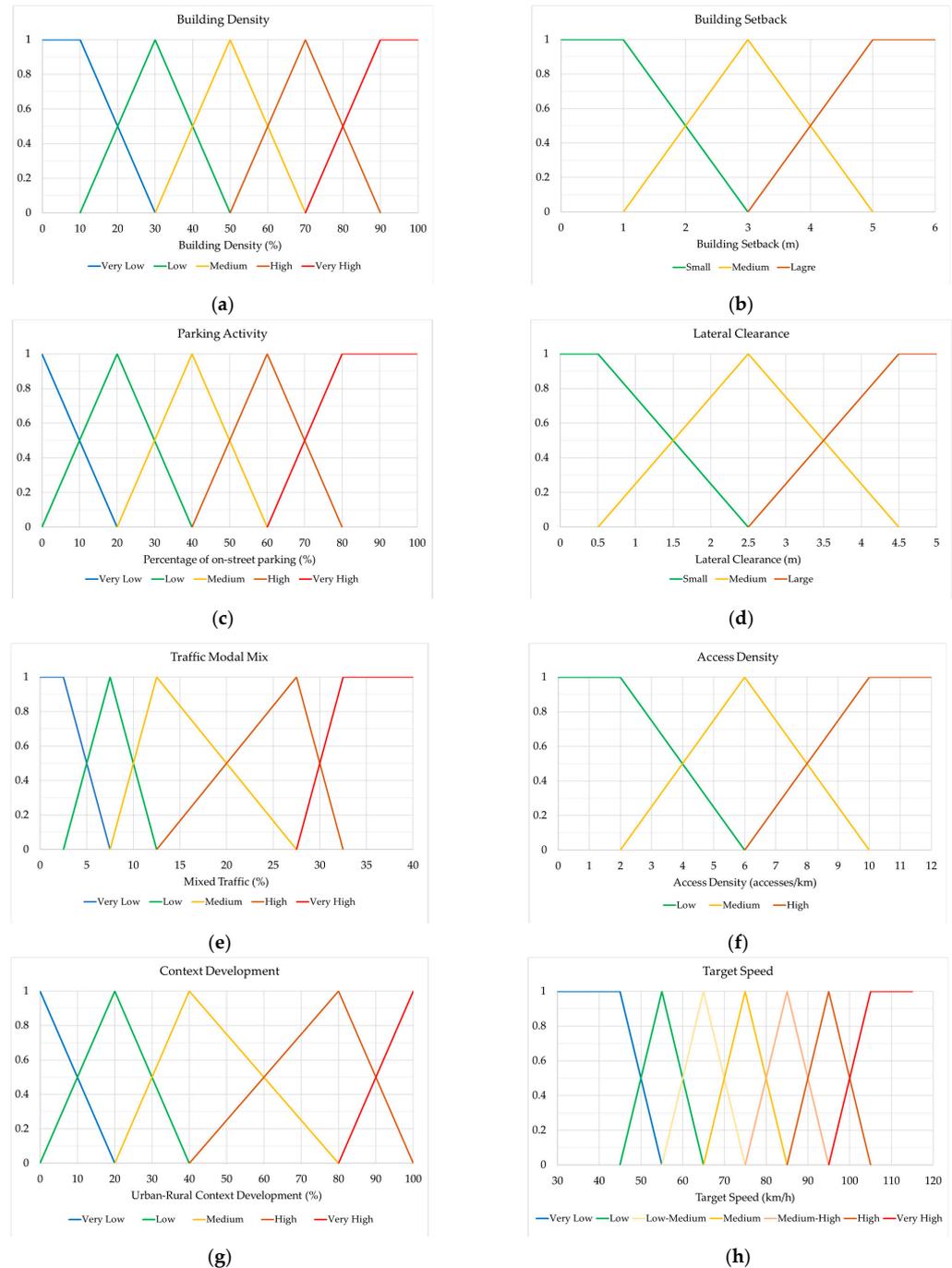


Figure 5. The membership functions associated with input and output variables: (a) building density; (b) building setback; (c) parking activity; (d) lateral clearance; (e) traffic modal mix; (f) access density; (g) urban–rural context development; (h) target speed.

3.3.3. Fuzzy Rules

Fuzzy rules were created from the experts’ opinions extracted from questionnaire surveys. Based on questionnaire surveys, a video of the multilane highway segment was presented to all the experts, one at a time. Each expert was asked to attribute linguistic values to the input variables and to identify the roadway contexts (R, SL, SH, U, or UC) and target speed (ranging from ≤ 50 km/h to ≥ 100 km/h with 10 km/h incremental intervals) for 30 random highway segments. The experts’ opinions were analyzed, and fuzzy rules for context and speed classifications were developed. The Fuzzy Inference Systems were composed of 31 rules for context classification (FIS-I) and 69 rules for speed classification (FIS-II). Examples of fuzzy rules for FIS-I and FIS-II are presented in Tables 4 and 5, respectively.

Table 4. Examples of fuzzy rules for context classification (FIS-I).

Rule	IF—Clause			THEN—Clause
	Building Density	Building Setback	Parking Activity	Context Development
1	Very High	Few	Very High	Very High
2	Very High	Few	High	High
3	Very High	Medium	High	High
4	Very High	Medium	Low	Medium
5	High	Few	Medium	Medium
6	Medium	Few	Medium	Medium
7	Medium	Medium	Low	Low
8	Low	Medium	Very Low	Low
9	Very Low	Medium	Very Low	Very Low
10	Very Low	Large	Very Low	Very Low

Table 5. Examples of fuzzy rules for target speed classification (FIS-II).

Rule	IF—Clause				THEN—Clause
	Context Development	Lateral Clearance	Traffic Modal Mix	Access Density	Target Speed
1	Very High	Few	Very High	High	Very Low
2	High	Few	High	High	Low
3	High	Medium	Medium	High	Low
4	Medium	Few	High	Medium	Low–Medium
5	Medium	Few	Medium	Low	Low–Medium
6	Medium	Medium	High	Medium	Medium
7	Low	Medium	Medium	Low	Medium
8	Low	Large	Medium	Medium	Medium–High
9	Very Low	Medium	Low	Low	High
10	Very Low	Large	Very Low	Low	Very High

3.3.4. Evaluation of Contexts and Speeds

The final step of the FIS method is to reason input data through numerical operations and estimate the outcomes. In this study, the outcomes were (i) the roadway context measured by the degree of urban–rural context development (ranging from the lowest development of 0% or rural to the highest development of 100% or urban) and (ii) the target speed (from ≤ 50 km/h to ≥ 100 km/h).

FIS aggregates the numerical scores for different input attributes, x_i^* s, and produces a score for the output attribute z^* . The inference system has the following format.

- Premise: $x_1 = x_1^*, x_2 = x_2^*, x_3 = x_3^*$.
- Rule 1: If (x_1 is A_1) and (x_2 is B_1) and (x_3 is C_1), then z is D_1 .
- Rule 2: If (x_1 is A_2) and (x_2 is B_2) and (x_3 is C_2), then z is D_2 .
- ...

Conclusion: $z = z^*$.

Where x_1^* , x_2^* , and x_3^* are the values of input attributes. The t-norm operation was chosen as the AND operator in the evaluation process. The mathematical operations of the inference system with n rules are as follows in Equation (2).

$$A(z) = \max_{k=1,2,\dots,n} \left[\min \left\{ \min \left(S_{X_1}^{(k)}(x_1^*), \dots, S_{X_n}^{(k)}(x_n^*) \right), A^{(k)}(z) \right\} \right] \tag{2}$$

where x_i = value of attribute i ($i = 1, 2, \dots, n$) and z = aggregated value of output. $S_{X_i}^{(k)}(x_i)$ and $A^{(k)}(z)$ are, respectively, the membership functions with the input variables and output variable associated with categories in reference to rule k , as illustrated in Figure 6. For each rule, the minimum degree of membership among the inputs in the premise $S_{X_i}^{(k)}(x_i)$ was determined and then applied to shape the membership function of the output $A^{(k)}(z)$. Finally, the centroid defuzzification method was used to determine the value of output z^* , as presented in Equation (3)

$$z^* = \frac{\int z \cdot A(z) dz}{\int A(z) dz} \tag{3}$$

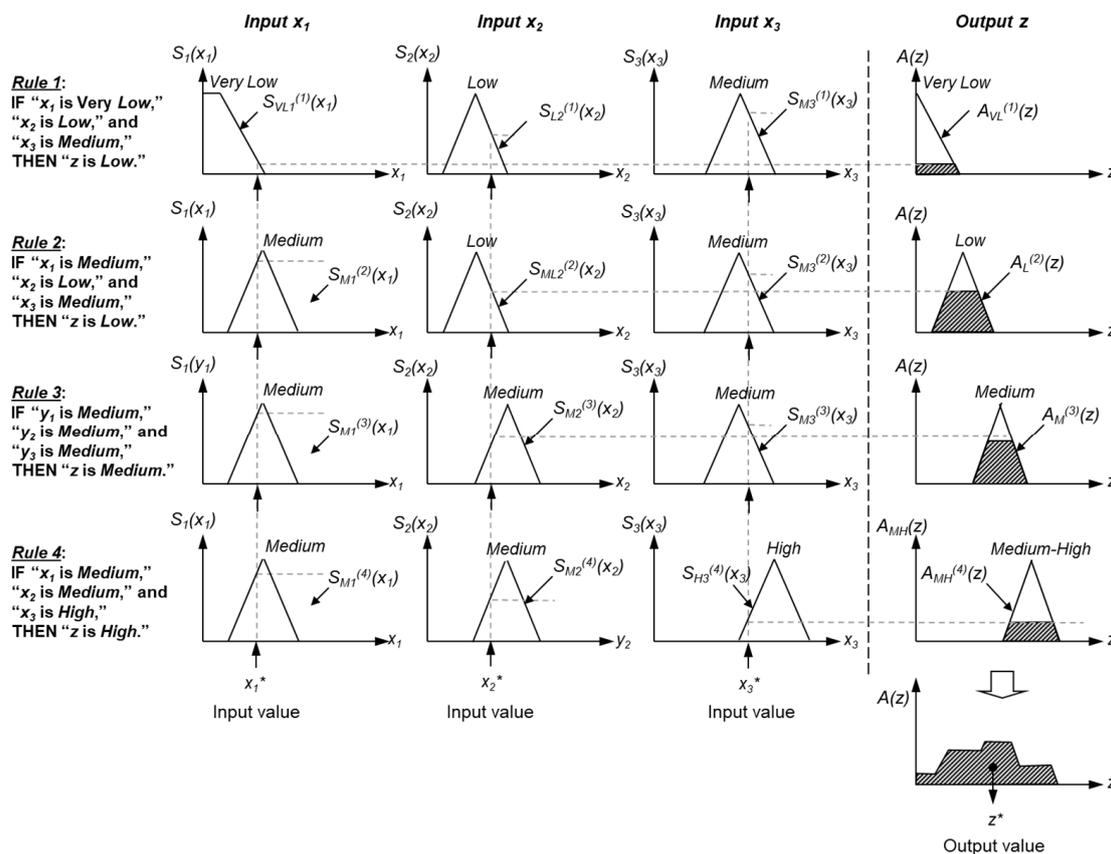


Figure 6. The mechanism of fuzzy inference of different input variables.

The proposed fuzzy expert system had two inference systems. The first FIS evaluated the degree of urban–rural context development from 0 to 100% to represent the class of roadway contexts (R, SL, SH, U, or UUC). The second FIS evaluated the numerical value of target speed and its class (≤ 50 km/h, 50–60 km/h, 60–70 km/h, 70–80 km/h, 80–90 km/h, 90–100 km/h, and ≥ 100 km/h).

4. Results and Discussion

This study developed a fuzzy expert system for the classification of roadway contexts and target speeds on multilane highway segments in Thailand. The results and discussion are presented in three respects: the model analysis, the model validation, and the model application.

4.1. Analysis of Contextual and Speed Classifications

The fuzzy expert system for the classification of roadway contexts and target speeds was designed and developed based on data from expert opinions and field investigations associated with selected multilane highway segments in Thailand's highway network. The input variables were decided based on experts' consensus. Data related to input variables were obtained based on the validated estimation of experts and the calculation of analysts. The membership functions of variables and fuzzy rules were created from experts' opinions extracted from the questionnaire surveys.

The fuzzy expert system used three input variables, including the building density, building setback, and parking activity, to evaluate the roadway contexts in terms of the degree of urban–rural context development. Furthermore, the system used the estimated roadway context together with the other three input variables, including the lateral clearance, traffic modal mix, and access density, to evaluate the target speeds.

The analysis presented four categories of contextual classification, i.e., rural highways (R), low-density suburban highways (SL), high-density suburban highways (SH), and urban highways (U). More than 70% of highways in Thailand are suburban highways, 20% are in rural contexts, and 10% are in urban contexts. It is noted that highways in urban core contexts (UC) were not found in a highway network. The analysis presented seven ranges of target speed classification, i.e., ≤ 50 km/h, 50–60 km/h, 60–70 km/h, 70–80 km/h, 80–90 km/h, 90–100 km/h, and ≥ 100 km/h. When considering both classifications, some categories were nonexistent. Finally, the fuzzy outputs categorized the roadway contexts and target speeds into 11 classes, including $U \leq 50$, U60, SH60, SH70, SH80, SL70, SL80, SL90, R90, R100, and $R > 100$.

Figure 7 shows the four examples of multilane highway segments with all input data and the fuzzy outputs of roadway context and target speed.

4.2. Validation of Fuzzy Inference Systems

The validation of the model was performed by comparing the classes of roadway contexts and target speeds derived from the fuzzy expert system and expert opinions. The study categorized the roadway contexts and target speeds into 11 classes, including $U \leq 50$, U60, SH60, SH70, SH80, SL70, SL80, SL90, R90, R100, and $R > 100$. The study developed a confusion matrix (also called a matching matrix), as shown in Table 6. This matrix presents how many outputs from the expert system are consistent and inconsistent per class with those from expert opinions. The comparison shows that the overall accuracy is 90.8%, i.e., 109 out of 120 segments were correctly classified as located along the upper-left to lower-right diagonal of the matrix. In addition, a Chi-square test was performed to prove the consistency of roadway contexts and target speed estimates. The statistical analyses show that the Chi-square values for context and speed categories are both lower than the critical value. It shows a reasonable estimation of contextual and speed classifications of highway segments.



Figure 7. Examples of inputs and outputs from the fuzzy expert system for given highway segments.

Moreover, the results found that among the 11 mismatches, 6 are of roadway contexts, 3 are of target speeds, and 2 are of both. The fuzzy expert system classified the target speeds more accurately than the roadway contexts. This may imply that more contributing factors used for contextual classification are required for better estimation.

It should be noted that the target speed is the recommended maximum speed at which the designers expect road users to operate on a given highway segment in a specific context and given roadside activities. This study compared the estimated target speeds from fuzzy outputs with the observed operating speeds along 120 multilane highway segments. Figure 8 shows the scatter plot between the target speeds and the operating speeds. The figure shows that the operating speeds lie above the 45-degree line. The operating speeds tend to be higher than the target speed, and there was a statistically significant difference between the operating speeds and the target speeds ($t\text{-stat} = 12.7$ at 95% confidence interval). Therefore, the findings indicate that the operating speeds do not align with the safe target speeds. The roadway design and speed management on existing highway segments should be upgraded by considering the context patterns and roadside activities.

Table 6. The confusion matrix comparing the classes of roadway contexts and target speeds derived from the fuzzy expert system and expert opinions.

Context and Speed		Expert Opinions											Total
		U	U	SH	SH	SH	SL	SL	SL	R	R	R	
		<50	60	60	70	80	70	80	90	90	100	>100	
Fuzzy Expert System	U <50	1	0	0	0	0	0	0	0	0	0	0	1
	U 60	0	5	0	0	0	0	0	0	0	0	0	5
	SH 60	0	1	12	0	0	0	0	0	0	0	0	13
	SH 70	0	0	0	19	1	1	0	0	0	0	0	21
	SH 80	0	0	0	0	18	0	1	0	0	0	0	19
	SL 70	0	0	0	1	0	10	0	0	0	0	0	11
	SL 80	0	0	0	0	1	0	11	1	1	0	0	14
	SL 90	0	0	0	0	0	0	0	16	0	0	0	16
	R 90	0	0	0	0	0	0	1	1	8	1	0	11
	R 100	0	0	0	0	0	0	0	0	0	7	0	7
	R >100	0	0	0	0	0	0	0	0	0	0	2	2
	Total		1	6	12	20	20	11	13	18	9	8	2

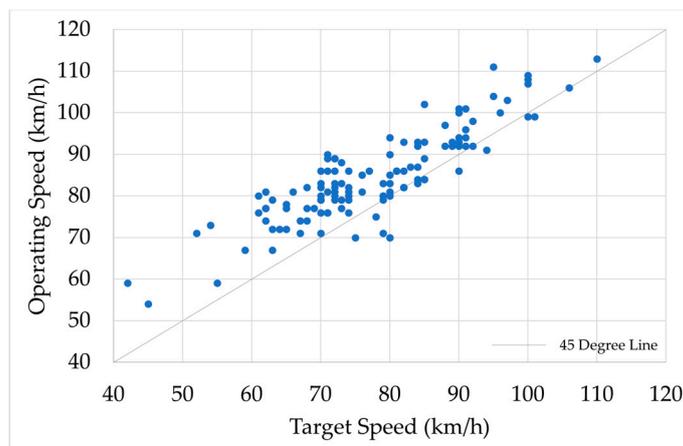


Figure 8. Scatter plot between the target speeds and operating speeds.

4.3. Applications to Roadway Contexts and Target Speeds on Highway Network

The proposed fuzzy expert system was applied to multilane highway networks in Thailand. The example of multilane highway classification in Petchaburi city and neighboring districts within Petchaburi province is presented here. Data related to roadway and roadside environments were taken from the Highway Information System, Geographic Information System databases, and Google Street View.

Figure 9 displays the classification of multilane highway segments of the case study. The context classification (U, SH, SL, R) is shown in Figure 9a, and the target speed classification (from 50 to 100 km/h) is shown in Figure 9b. The maps separately show the variability of roadway contexts and target speeds.

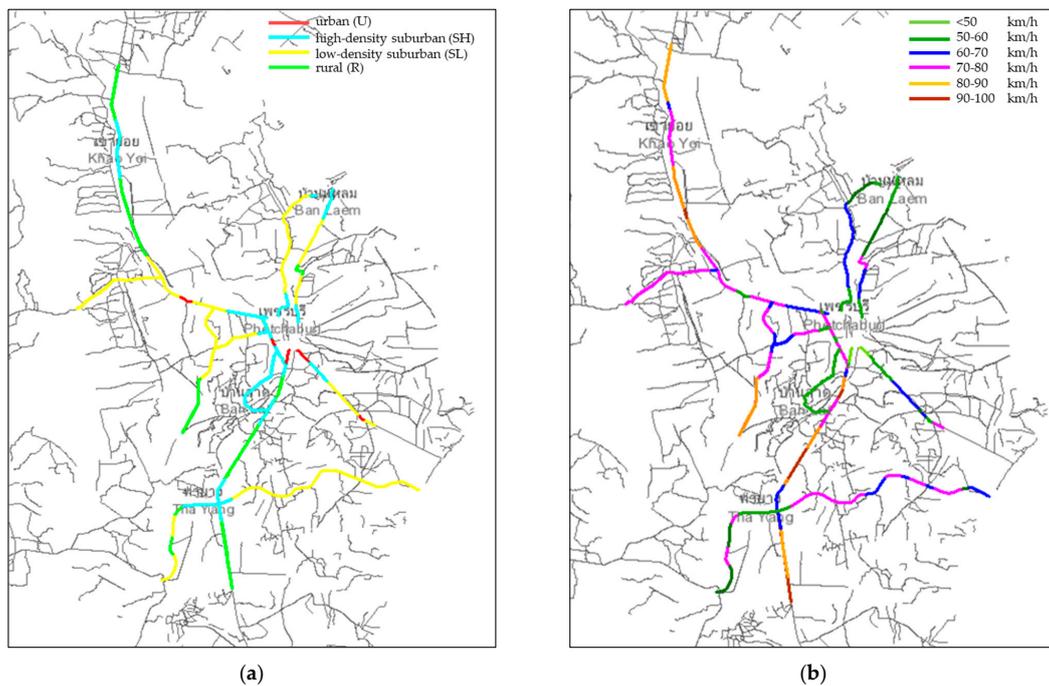


Figure 9. Example of highway network maps classified by (a) roadway context; (b) target speed.

Figure 10 presents the classes of multilane highway segments by roadway contexts and target speeds. This map indicates the transition areas where the classes are altered. The system can help decide whether the roadway and roadside design and speed management are aligned with the existing highway and speed classification to ensure safe operations on a highway.

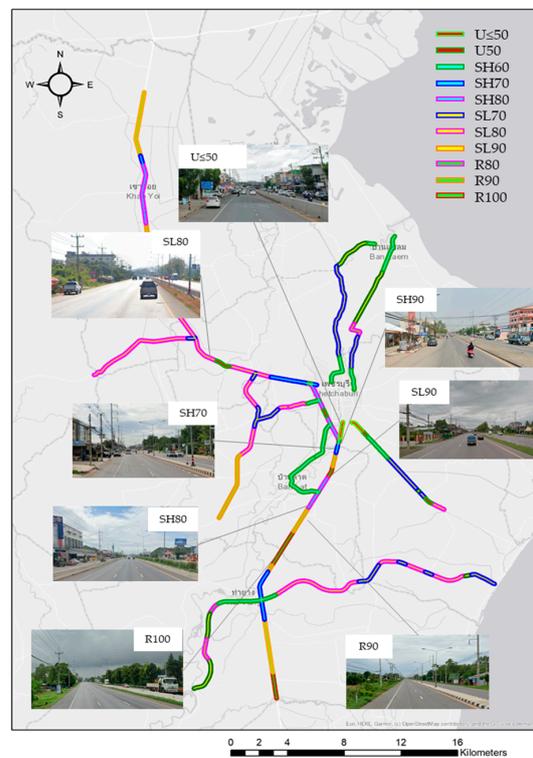


Figure 10. Example of highway network map classified by roadway contexts and target speeds.

5. Conclusions

The highway classification system is a fundamental tool for roadway infrastructure management. The classifications of highway type and speed are important design principles of highway infrastructure in all stages of the highway development process. Recently, there has been a new concept of highway classification, which considers roadway contexts to reflect the expectations of road users and the changes in land use [6]. Contextual classification is the process of differentiating highway segments based on environmental contexts. Speed classification is the process of designating the appropriate target speed for given highway segments based on roadway characteristics and the roadside environment. Based on literature reviews, there were, however, no general measures, no universal descriptors for each class, and no consensus analytical methods used for this highway classification system. Additionally, most variables used are linguistic (e.g., low activity, high density), and the dependencies between them (e.g., low vs. high) are vaguely defined. A new technique that accounts for the ambiguity in the process of selection and evaluation is necessary.

This study proposed the fuzzy expert system as a classification method under uncertainty to identify the roadway context and to establish the target speed of multilane highway segments in Thailand's highway network. This expert system can appropriately capture the imprecision of multiple input factors and accurately reflect the subjective judgments inherent in highway and speed classification problems. The methodology used in this study is two-fold: (i) identifying factors affecting roadway contexts and target speeds, and (ii) evaluating contextual and speed classifications based on contributing factors. This study used the Fuzzy Delphi method for screening the potential factors influencing roadway contexts and target speeds. This study used the bi-level Fuzzy Inference System method for classifying multilane highway segments according to roadway contexts and target speeds. The first model evaluated the contexts of the highway segment and then input it to the second model for identifying the target speeds of a given highway segment. The proposed method was validated by experts' opinions and applied to the real-world highway network.

This study creates new opportunities for both planning practice and academic research by addressing limitations associated with traditional highway classification systems. This research is an initial investigation of highway contextual and speed classifications in Thailand where highways and land uses are not well-integrated into a planning process and where they are under mixed-traffic conditions. The proposed methodology is systematic and flexible. The knowledge base was logically built by using the membership functions to accommodate the choices of inputs and using the rules to accommodate the particular decision. Therefore, the fuzzy expert system developed in this study can be used to assist highway planners in precisely identifying contexts and target speeds for a particular facility. It can also help highway designers devise appropriate context-sensitive solutions in safe highway design and speed management.

Although this study provided meaningful findings, some limitations need to be considered in future work. Firstly, the classification system was developed based on existing multilane highways as principal or minor arterials. Future studies should verify its applicability to other road functions and types (e.g., freeways, two-lane highways, or local streets) and other stages of highway development (e.g., in the design stage). It should also be noted that the proposed expert system is a decision-making tool to support contextual and speed classifications in this study, and the outputs should be further adjusted by the experts under local conditions if necessary. Secondly, this study identified contributing factors based on expert opinions and past studies, and the model was analyzed based on limited input attributes and experts. Some inputs may be highly correlated. In future studies, this issue should be investigated, and a sensitivity analysis should be performed to determine the optimal number of factors used and the membership functions, if data are available. Finally, this study focused on fuzzy methods in the evaluation process. Future studies may benefit from a comparison of advantages and shortcomings with other

analytical methods. A comparative analysis of these methods can increase the credibility and robustness of the research.

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