Developing a fuzzy-based decision-making procedure for traffic control in expressway congestion management

Trinh Dinh Toan[a*], Yiik Diew Wong[b], Soi Hoi Lam[c], Meng Meng[d]

[a] *Department of Transportation Engineering, Thuyloi University, 175 Tay Son, Dong Da, Hanoi, Vietnam*
[b] *School of Civil and Environmental Engineering, Nanyang Technological University of Singapore, 50 Nanyang Avenue, 639798 Singapore*
[c] *Department of Civil and Environmental Engineering, University of Macau, Avenida da Universidade, Taipa, Macau, China*
[d] *School of Management, University of Bath, Bath, BA2 7AY, UK*

[*]*Corresponding author, Email: Trinhdinhtoan@tlu.edu.vn*

Abstract. This paper presents part of a multi-stage fuzzy logic controller (MS-FLC) that is developed for traffic control in congestion management on expressways. The decision-making process of traffic control for expressway congestion management using the MS-FLC consists of three tasks: (1) evaluation of current traffic congestion; (2) prediction of traffic congestion tendency; and (3) recommendation of control strategies and control actions to alleviate the congestion. This paper presents the 3rd stage of the MS-FLC that develops a fuzzy-based decision-making procedure (FDMP) for management of recurring and non-recurring congestion. Using fuzzy rules, the FDMP evaluates the current and anticipated traffic data and incident information to recommend control strategies at the strategic level, and control actions at the operational level. Results from this research show that: (i) the FDMP offers a comprehensive procedure in deriving control strategies and actions; (ii) FDMP control actions are derived from a systematic decision-making logic where the design of control rules is consistently oriented toward achieving desirable control objectives; (iii) the FDMP targets a proper balance in congestion management between the mainline and the ramp using compromise rule design; (iv) the FDMP facilitates using various forms of available traffic and incident data on an extended expressway segment to derive at control actions, making the system-wide gains possible; and (v) the FDMP could be applied for management of both recurring and non-recurring congestion.

Keywords: fuzzy logic; fuzzy rule base; decision making; traffic control; ramp metering; congestion management

1. Introduction

Traffic control on expressways can be classified into local, coordinated, and integrated control strategies [1-3]. Local control makes use of local measurements of traffic variables to calculate ramp metering flows for a specific ramp. Coordinated control incorporates operational activities and simultaneously calculates ramp flows for controllable ramps along an expressway corridor. Integrated control deploys various types of control measures such as ramp metering and route diversion to promote synergistic effects [3-6]. Previous research showed that local ramp control is the most direct and effective control measure in relieving expressway traffic congestion for the majority of applications, while coordinated and integrated controls should be considered if congestion is widespread over extended expressway corridors. However, coordinated and integrated controls may provide system-wide benefits over local control because more extensive information is used and more robust control actions are coordinated and applied [7,8]. Nevertheless, for complicated situations, determining the appropriate type of control is not straightforward since this depends on network topology, background congestion level, and the availability of control facilities [9].

Common control measures that are employed in expressway networks include ramp control, link control, and driver information and guidance systems [3,10]. Ramp control applies devices such as metering signals to regulate the number of vehicles entering the expressway [11,12]. Ramp control is the most efficient and popular measure to control expressway traffic [3,7,10,13,14]. Ramp control strategies can be fixed-time or traffic-responsive [3,8,10]. The former derives the ramp metering rates off-line over different periods of the day using historical data, and are applied for repeatable and steady-state traffic conditions. The latter adjusts the ramp metering rate to take account of traffic dynamics in a reactive or proactive manner [8,9].

Decision-making process of traffic control on expressways involves several important tasks, including determining control strategies, selecting control measures, and setting control actions [9]. The control process can be conducted manually by a traffic operator, or automatically by a control algorithm. In manual control, the operation is dependent on operators' judgment and decision, thus the control operator must acquire good knowledge and experience, and should be able to quickly perform an analysis of the current traffic conditions in order to make appropriate decisions and carry out control actions [9,15]. Given the high time pressure and cognitive limits, the manual control incurs potential lack of structured, rational, and uniform solutions from time to time [9,16]. The automatic control [17-20], on the other hand, can automate control process to offer structured solutions, however it does not include an explanatory instrument to assist the operator in determining appropriate control strategies, measures, and actions. The automatic control also lacks flexibility to deal with inherent nature of traffic control problems such as uncertainty and missing/incomplete data.

In essence, traffic control on expressways is a complicated multivariable problem. In a short time-window, the control operator must handle large amount of current and forecasted data and information to make control decisions on a real-time basis. The control decision-making process typically evolves from a low-to-high level of abstraction that includes data manipulation, information processing and engineering judgement. Decisions on expressway traffic control include both structured decisions and unstructured decisions [9,15,21]. Structured decisions are associated with established routine contexts such as recurring congestion that is characterized by a well-defined operating procedure. Unstructured decisions are associated with emergent contexts or non-predictable events such as non-recurring congestion, where the operating procedure is ill-defined and decision making is highly intuitive. For these reasons, it is critical to deploy a decision support system (DSS) that includes an intelligent computerized module for manipulating various types of data and information to avoid operator's cognitive overload and to support decision-making. In a DSS architecture, the computer provides data processing power to establish recommended solutions in a structured and consistent manner, while the human provides subjective judgements on qualitative information to make decisions [22,23].

Decisions on expressway traffic control are often made in the face of vagueness and uncertainty that arise due to various reasons, including imprecise data measurement, approximate information reasoning, inaccurate traffic prediction, and imprecise human perception [15,24,25]. Due to the complicated and uncertain nature, decision-making for expressway traffic control often requires robust techniques that deal efficiently with the problem of uncertainty and fuzziness, in association with human judgement. Fuzzy logic is a qualitative approach that is close to human observation, reasoning and decision-making. A fuzzy logic system (FLS) is a non-linear mapping of input to the output universe of discourse using fuzzy logic principles [25,26]. FLSs provide foundations for incorporating fuzzy reasoning with engineering judgement for handling both numerical data and linguistic information.

Fuzzy logic control is a control law described by a rule-based system with vague predicates and a fuzzy logic inference mechanism [27]. A fuzzy logic controller (FLC) provides a means to convert a linguistic control to an automatic control strategy. Fig. 1 shows the conceptual diagram of a FLC. A standard FLC consists of 4 components:

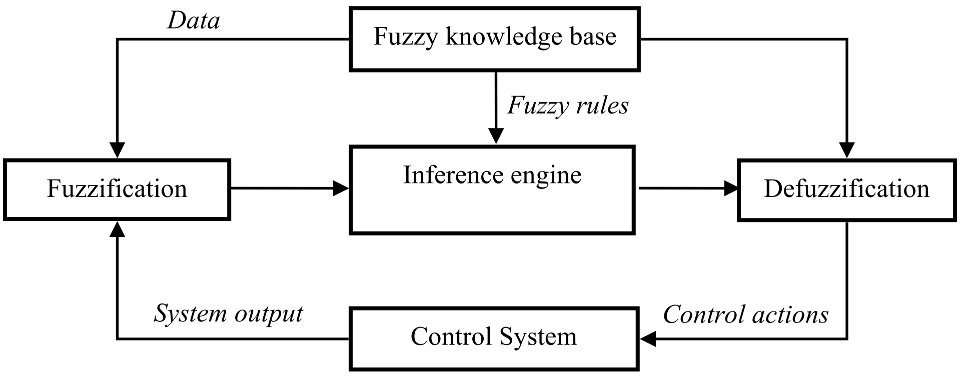

Fig. 1. Conceptual diagram of a FLC

(i). The fuzzification measures the values of input data and performs a scale mapping that converts the data into suitable linguistic values with associating membership degrees.

(ii). The fuzzy knowledge base comprises knowledge of the application domain. It consists of a database and a fuzzy rule base. Basically, the fuzzy rule base characterizes the control policies of the system in the IF-THEN format.

(iii). The inference engine is the kernel of a FLC. It has the capability of simulating human decision making based on fuzzy concepts and the capability of inferring fuzzy control actions employing the rules of inference. The inference engine performs the interpretation of the sentence connectives AND and OR to calculate the degree of fulfilment of each rule, then the conclusions of all active rules are aggregated using the MIN or MAX operator.

(iv). The defuzzification converts the aggregated values of control variables into single crisp values using one of defuzzification methods, including the Centre-Of-Area (COA), the Mean-Of-Maximums (MOM), and the First-Of-Maximum (FOM). The most frequently used technique is the COA method that finds the central point of the aggregated outputs.

Fuzzy logic is the most suitable means for representing qualitative information and handling uncertainty problems [9,28,29], and is widely used for DSSs [30-33]. The rationales for applying fuzzy logic for development of a DSS for traffic control for congestion management on expressways include: (i) linguistic expressions are general and easy to be perceived by the traffic operator; (ii) the transition from one fuzzy set to another is gradual, representing continuity in human perception; and (iii) the capability to incorporate quantitative numerical data with qualitative information to provide a single output that is convenient for decision-making [25,29,34].

Traffic control is one of the earliest applications of FLSs in traffic engineering [16,25,35,36]. Chen et al. [37] proposed an ingenious ramp control strategy following fuzzy control approach. The proposed method was evaluated in comparison with existing controllers under six incident scenarios. The results showed a potential to obtain higher ramp control efficiency with quick response to various incident cases. Xu et al. [38] proposed a local fuzzy logic controller-based (FLC) ramp metering algorithm for solving the optimal freeway local ramp metering problem. The results showed that the proposed approach was promising in obtaining the optimal freeway local ramp metering strategies to strike a balance between traffic conditions on the mainstream and the on-ramp link. Taylor and Meldrum [39] presented a fuzzy logic ramp metering algorithm that was implemented on 126 ramps in the greater Seattle area. The FLC was evaluated with the Local Algorithm and the Bottleneck Algorithm over a four-month period. The results showed that the FLC had lower mainline occupancies, higher throughput volumes, and slightly higher queues than the Local Algorithm, and better queue management than the Bottleneck Algorithm. These outperformances were due to the FLC's ability to balance conflicting objectives, and to use smooth control in a preventative manner. Tariq et al. [16] investigated the process of updating the signal timing plans during non-recurrent conditions by capturing the history of the responses of the traffic signal engineers and utilizing this experience to train a machine learning model. The simulation results indicated that changing the green times based on the output of the fuzzy rules decreased delays caused by lane blockages or demand surge. Other FLS applications for traffic control can be seen in [9,16,25]. In general, previous research studies have taken advantage of fuzzy logic approach in dealing with multi-variable traffic control problems, and the results have been promising. However, while there has been a lot of research work on the use of fuzzy logic for traffic control, most of the work focused on local and reactive control, and little effort has been devoted to FLC approach in traffic control for incident management. Essential issues such as evaluation of the current traffic state and anticipation of the incoming traffic condition to establish a systematic procedure in deriving control strategies and control actions with the aid of a DSS have not been adequately explored.

Herein, we are motivated to conduct a broader research study that develops a multi-stage fuzzy logic controller (MS-FLC) for traffic control in congestion management on expressways. The MS-FLC development roadmap starts from the local control to corridor-wide control, for which the performance of initial development has been successfully evaluated and the results presented in [12]. The MS-FLC consists of 3 stages: (1) evaluation of existing traffic congestion; (2) prediction of incoming traffic congestion; and (3) recommendation of control strategies and control actions. Specifically, this paper presents development of a fuzzy-based decision-making procedure (FDMP) for traffic control for congestion management on expressways, which corresponds to the 3rd stage of the MS-FLC. The purpose of the FDMP is to provide structured and consistent solutions to the traffic operator at both the strategic and operational levels.

The structure of this paper is as follows: Section 2 briefly describes the overall decision-making procedure and its components; Sections 3 explains the input and output variables of the rules, establishes the rule formation for control strategies and actions, and provides discussions; Section 4 summarizes the conclusions and findings from the research study.

2. Decision-making logic

2.1 Overview

Fig. 2 illustrates the overall decision-making process for traffic control on expressways, presented in the MS-FLC. The process involves three stages:

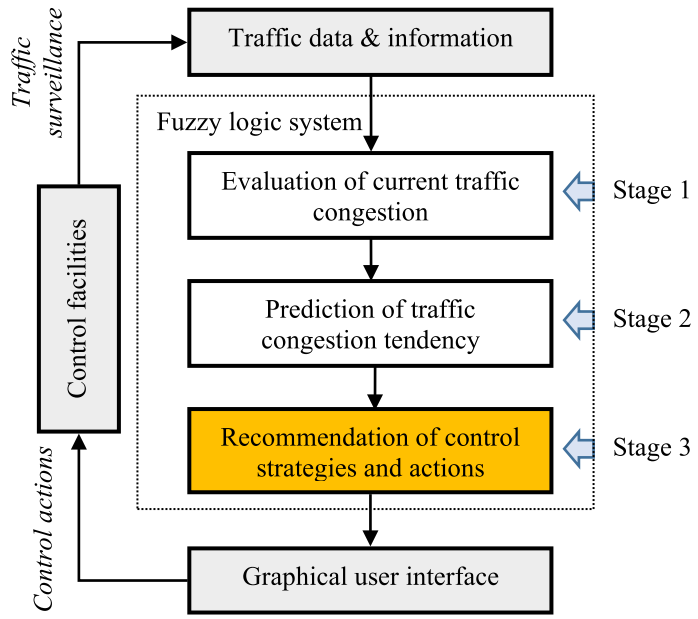

Fig. 2. Overall decision-making process for expressway traffic control

Stage 1: Evaluation of the current traffic congestion: This stage involves evaluation of the prevailing state of existing traffic on the expressway mainline downstream of the ramp. The state of traffic is characterized by an abstract term known as "congestion level" that reflects the severity of traffic congestion, and is evaluated using speed and density variables. The rules in this stage can be categorized as *fact-state rules* since the reasoning logic uses numerical data to evaluate the state of traffic.

Stage 2: Prediction of traffic congestion tendency: This stage involves prediction of the *change in state* of traffic. Given the outcome from the first stage, the second stage continues to anticipate the traffic conditions in the immediate future, using time-series short-term traffic prediction. The rules in this stage are typically *state-state* rules, since the reasoning sequence infers the future state from the current state using external variables from the traffic-forecasting module.

Stage 3: Recommendation of control strategies and actions: Given the outcomes from the first two stages, the MS-FLC performs a sequential analysis to arrive at recommended solutions. Given this reasoning process, the rules in stage 3 pertain to both strategic level (for control approach and control strategy) and operational level (for control action). The traffic operator may consider local, coordinated, or integrated control strategy, and given the selected control strategy the system recommends an appropriate level of ramp metering rates in a time-series fashion. During the control implementation, the traffic surveillance system continually observes and provides updated data and information to the MS-FLC, and the ramp metering rates are adjusted accordingly. The rules for control actions are basically *state-action* rules for the given input-output mapping.

This research focuses on developing the FDMP for control strategies and control actions in the 3rd stage (Fig. 3) of the MS-FLC. The stage receives the current traffic congestion level as output from the 1st stage. Depending on the criticality of the congestion, the MS-FLC continues into the 2nd stage – prediction of traffic tendency or proceeds to the 3rd stage – recommendation of control strategies and control actions wherein if the congestion is critical, urgent control interventions need to be implemented immediately, and the rules in the 3rd stage are executed. In contrast, if the traffic congestion is not yet critical, the system proceeds with traffic forecasting module, and rules in the 2nd stage will be fired with the forecasted data to provide anticipated congestion level for the 3rd stage.

The 3rd stage consists of three blocks: intervention level, control strategy, and control action. The *intervention level* indicates how strong the control intervention should be. The *control strategy* represents the control approach and appropriate countermeasures to deal with the congestion problems. The strategy stands for the *supply side* [40] that utilizes available resources in response to the evaluated intervention level. It provides a broad methodological outlook in confronting with the congestion problems, upon which specific control actions are implemented. Finally, the *control action* reflects a collection of specific control settings, given the selected control strategy. Examples of control actions include ramp metering setting, queue management, diversion action, and message dissemination.

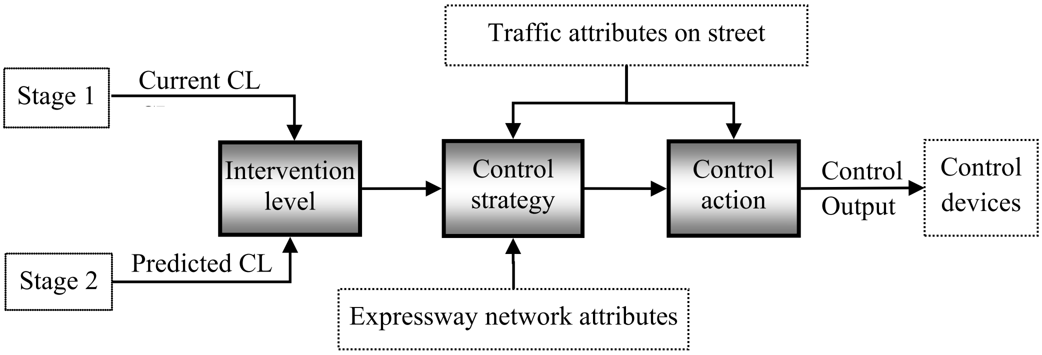

Fig. 3. Schematic sequence of the 3rd stage of the MS-FLC

Fig. 4 elaborates the decision-making sequence of the FDMP, starting from traffic condition to intervention level, control strategy and control action. From the systematic perspective, the current/predicted congestion level (CL) and intervention level are the inputs of FDMP, control approach and control strategy are intermediate components that support making strategic decisions, and control action is the system output that recommends making decisions at the operational level. The control approach represents the magnitude or scale of control, and is a transitional step of the methodological outlook that rationalises the selection of control strategy based upon the intervention level. The approaches of control are categorized into “No control”, “Local control”, and “Corridor-wide control”. Specifically, “No control” associates with “No intervention”, “Local control” associates with “Slight” and “Moderate” intervention levels, and “Corridor-wide control” associates with “Strong” and “Very Strong” intervention levels.

The control strategies include several options, including “Local ramp control”, “Coordinated ramp control”, and “Integrated control”. “Local ramp control” corresponds to the local control scale where the mainline traffic demand upstream of the ramp is low, and the queue on the ramp is short. “Coordinated ramp control” and “integrated control” are associated with the corridor-wide control scale when the mainline traffic demand is medium-high, but the former is recommended when there is a medium queue on the onramp and the diversion route is congested, while the latter is recommended when there is a long queue on the onramp and the diversion route is not congested. During the operation, the control approach and control strategy can be shifted if there is sustained change in the traffic situation on the expressway and the ramps as well as the affected diversion routes.

Regarding the control actions, the “Local ramp control” and “Coordinated ramp control” strategies mobilize only the ramps for traffic control, while the “Integrated control” utilizes different measures, essentially ramp control and route diversion (via variable message sign, VMS), to enhance the promoted synergistic control effects. Given the selected control measures, the FDMP calculates the ramp rate that should be discharged onto the expressway mainline in each time interval, using the input variables presented in Section 3.1.

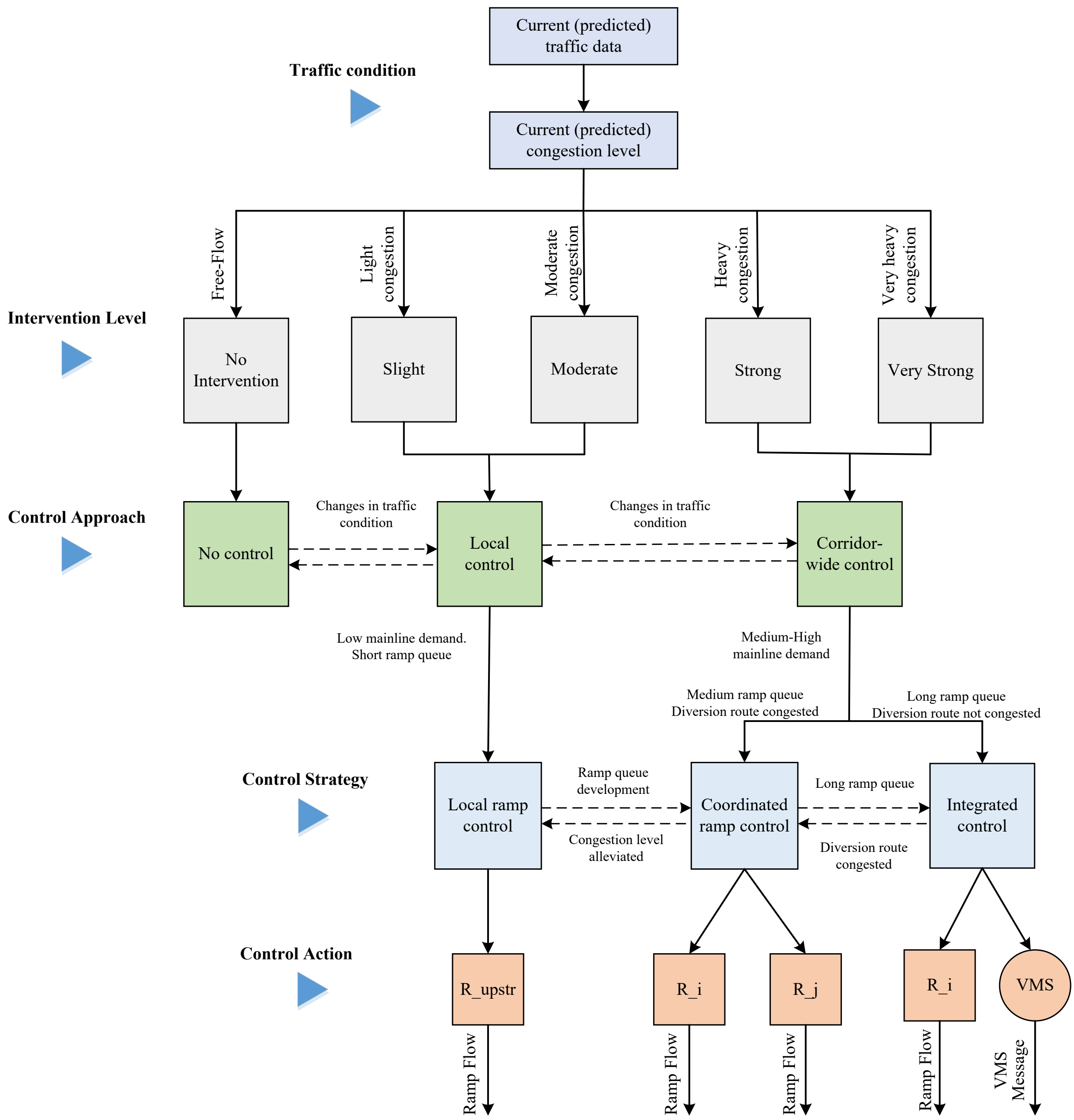

Fig. 4. Decision tree of the FDMP

2.2 Intervention level

The intervention level reflects the strength of the intervention control that should be applied in association with the prevailing or anticipated traffic condition. The block is a resulting blend of two control modes, *i.e.* reactive control that uses the current real-time traffic data, and proactive control that uses the predicted traffic data.

Input variables

This study uses density and speed as the input parameters to evaluate congestion level: density reflects freedom to maneuvers as related to service quality, and speed is a major concern of drivers as related to traffic dynamics. They are both quantitative measures that characterize operational conditions of a traffic stream on the expressways. The use of both of speed and density is necessary to better represent the operational conditions of expressway traffic [25,41].

The use of 2 inputs to evaluate an output (congestion level) is known as a multiple-input-single-output (MISO) system. In the MISO model, rules for the congestion level are characterized by two predicates in the antecedent, connected with an *AND* operator, and one predicate in the consequent. To represent the variables in a high resolution, we use the number of predicates $n_{x1} = n_{x2} = 5$, expressed by the following linguistic predicates:

$$V = \{VeryLow, Low, Medium, High, VeryHigh\} \quad (1)$$

$$K = \{VeryLow, Low, Medium, High, VeryHigh\} \quad (2)$$

and the linguistic predicates of the control variable are set as:

$$CL = \{FreeFlow,\ Light, Moderate, Heavy, VeryHeavy\} \quad (3)$$

The general expression of rules is of the form:

If speed is $V_{(x)}$ AND density is $K_{(x)}$ then congestion level is $CL_{(x)}$ (4)

that can be symbolically represented as:

$$\left(V \bullet V_{(x)}(v)\right)\Theta_{\min}\left(K \bullet K_{(x)}(k)\right) \rightarrow CL \bullet CL_{(x)}(v,k) \quad (5)$$

where the suffice (x) indicates any of the linguistic predicates in the corresponding variable.

Setting the boundaries of predicates of state variables (speed and density) is based on the ranges of speed and density stipulated in Exhibit 23-2 in the *Highway Capacity Manual* [42] while setting the boundaries of predicates of control variable (congestion level, Fig. 5) is made with reference to [43]. Specifically, *FreeFlow* indicates LOS A and partly LOS B, *Light* congestion indicates LOS C, partly LOSs B and D, *Moderate* congestion associates with the capacity-approaching operation (LOS E) and partly LOS D, where speed deceases significantly, density increases quickly with increasing flows, and maneuverability within the traffic stream is limited. *Moderate* congestion may also be associated with LOSs C and F with low membership degree. *Heavy* congestion indicates breakdowns in traffic stream, which can be considered LOS F at which queues start to form with potential propagation upstream, and being characterized by low speed and high density. Heavy congestion may also be associated partly with LOSs D and F. Finally, *VeryHeavy* represents a critical breakdown of flow of low-very low traffic dynamics, and is strictly associated with LOS F.

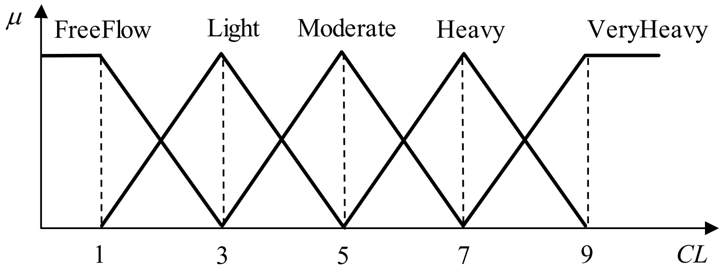

Fig. 5. Fuzzy partition of the congestion level

The relationships between speed and density are summarized in Table 1. It is worth noting that in Table 1 the elements marked with "---" represent speed and density relations that are not meaningful. Since in an uninterrupted-flow facility, the cause of congestion is internal [42], these combinations were removed because they are unlikely to occur.

Table 1. Rule decision matrix for congestion level
(FF: Free flow, L: Light congestion, M: Moderate congestion, H: Heavy congestion, VH: Very heavy congestion)

Density

Speed \ Relation	VeryLow	Low	Medium	High	VeryHigh
VeryLow	---	---	H	VH	VH
Low	---	M	M	H	VH
Medium	L	L	M	H	H
High	FF	L	M	M	---
VeryHigh	FF	FF	L	---	---

Source: Data from [25]

Output variable

The intervention level is imprecisely and empirically evaluated based on the input variables, and is normalized into a numerical domain [1 ÷ 10] with 5 fuzzy sets as follows (Fig. 6):

Int_Lev = {No, Slight, Moderate, Strong, Very_strong} (6)

No intervention means no control action needs to be carried out since the congestion effect can be negligible. More precisely, the traffic control is implemented as usual given the normal situation. This associates with favourable conditions of congestion management (light traffic demand, no capacity reduction under an incident occurrence, etc.) At the other extreme, *Very_strong* intervention level requires the maximum utilization of available resources to mitigate congestion. This intervention level is associated with critical congestion (heavy congestion, severe capacity reduction, high traffic demand).

Since the input variables independently coexist, the formation of rules in this block is straightforward: each condition of the rules is the union of several fuzzy sets, connected with an *OR* operator. The following describes 5 tentative rules for the intervention level:

R_1: If CL is Free_flow then Int_Lev is No

R_2: If CL is Light then Int_Lev is Slight

R_3: If CL is Moderate then Int_Lev is Moderate

R_4: If CL is Heavy then Int_Lev is Strong

R_5: If CL is Very_Heavy then then Int_Lev is Very_strong

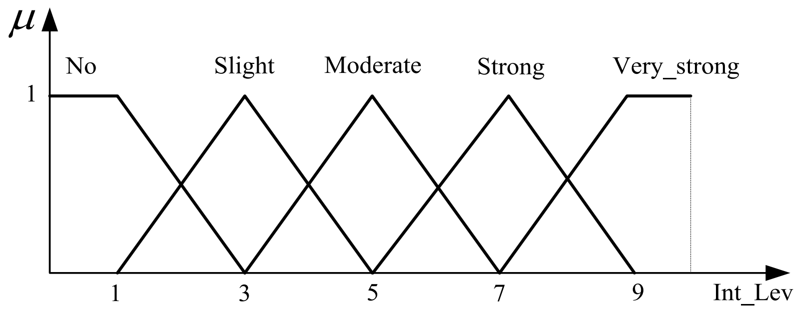

Fig. 6. Fuzzy sets of intervention level

Rules R_1 and R_2 define the first sub-domains of the intervention level, where predicted congestion level is free flow or slightly congested. The canonical format of the rules implies that given such forecasted states of traffic there would be no prevailing moderate, heavy congestion, or queue. Rules R_3, R_4, R_5, on the other hand, implicitly indicate that drastic control measures need to be implemented given the severe current or predicted congestion level, or the existence of queues on the expressway.

2.3 Control strategy

For the intermediate components, rules can be established using the direct mapping between the intervention level and the control approach and control strategy accordingly. In principle, the selection of control strategy should be made so that available resources are allocated cost-effectively. However, at this strategic level, the decision-making is essentially reliant on the domain knowledge of the traffic operator which is accumulated from daily control operation. Given the intervention level, the traffic control operator determines the control strategy considering the layout of the expressway, the location of control devices, and the traffic condition on the street network.

Intuitively, under normal situations such as a minor incident that causes only a local impact on the traffic, only slight or moderate intervention is required, thus a local control is triggered. In contrast, under heavy or very heavy congestion, strong or very strong intervention is required, and corridor-wide control must be considered. The determination of whether a corridor control should be coordinated or integrated is not straightforward. More specifically, the determination of the strategy for corridor control depends not only on the traffic and incident conditions in case there is a non-recurring congestion, but also on the network topology, on the availability of control facilities, and on the background congestion level on the street network. The following presents the methodology to determine the control strategy following corridor control as illustrated in Fig. 7.

Fig. 7 illustrates a basic hypothetical expressway segment with two on-ramps (ramp 1 and ramp 2) and an alternative route for diversion. The segment is divided into sub-segments with traffic sensors. A lane-closure incident is assumed to occur downstream of ramp 1 which causes congestion. To alleviate incident congestion, the control scheme considers three possible strategies. Let strategy 1 (ST1) denotes the local control implemented by ramp 1, strategy 2 (ST2) denotes the coordinated control implemented by the *coordination* of ramp 1 and ramp 2, and strategy 3 (ST3) denotes the *integration* of ramp 1 and route diversion. In addition, the integrated-control terminology can be extended to the scenario that mobilises both ramp 1 and ramp 2 and route diversion, denoted as ST3-ext. Assume that traffic and incident problems require corridor control. The question is to determine which strategy (ST2, ST3, or ST3-ext) is more suitable for control?

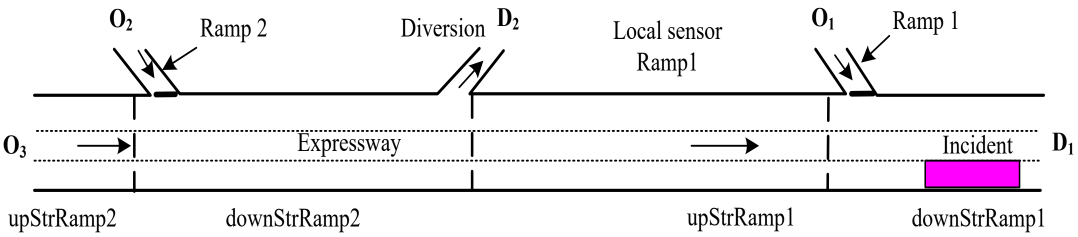

Fig. 7. Layout of an expressway section

In order to determine a viable control strategy, the knowledge on time-varying O-D demands is required. In Fig. 8a, O1, O2, and O3 denote the origins where traffic is generated from ramp 1, ramp 2, and the upstream mainline, respectively; D1 and D2 denote destinations at downstream of the mainline and the diversion route, respectively; $\beta_{ij}(k)$ (%) indicates the proportion of traffic generated from zone i and destined to zone j during interval k. In principle, the selection of control strategy should be made by considering the $\beta_{ij}(k)$ values. Assume that $\beta_{ij}(k)$ values are simply represented by two fuzzy sets Low and High (Fig. 8b).

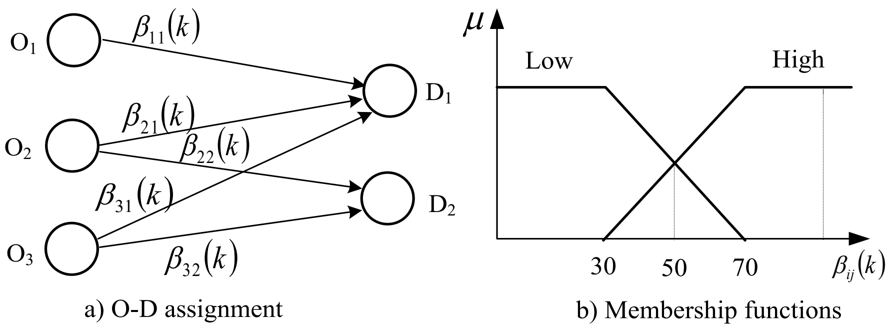

Fig. 8. OD assignment and membership functions

Accordingly, there are two possible situations that are associated with traffic demand upstream of ramp 1. If traffic demand upstream of ramp 1 is low, the implementation of corridor control is not justified. Hence, the assumption that the corridor approach is required associates with high upstream demand. The high demand upstream is the result of either high demand from ramp 2 (O2) or/and from the mainline (O3), denoted as $\beta_{21}(k)$ and $\beta_{31}(k)$ respectively. To alleviate the heavy congestion at the incident place, the arrivals upstream of ramp 1 should be managed by either regulating the entering flow at ramp 2 or/and diverging of traffic that is willing to take risk by proceeding to the incident place on the mainline. These concepts can be restated by three simple rules:

- If $\beta_{21}(k)$ is high then ST2
- If $\beta_{31}(k)$ is high then ST3
- If $\beta_{21}(k)$ is high AND $\beta_{31}(k)$ is high then ST3-ext

Alternatively, the decision can be made by considering the ratio of traffic demands from O2 and O3 that proceeds downstream to D1. Let $\xi_1(k) = V_{31}(k) / V_{21}(k)$ denote the ratio of flow rates from O3 and O2 to D1, respectively, during interval k. If the ratio is low the demand from ramp 2 is relatively high, the coordinated control will be more effective. By contrast, if the ratio is high the demand on the mainline upstream of ramp 2 is relatively high, the integrated control should be considered. It is worth noting that the terms "low" and "high" in this context are imprecisely defined. The above concept can be extended to an expressway system with n ramps and m diversion routes. However, the literature shows that the control facilities far upstream have little impact on the control scheme being considered.

For evaluating traffic condition (system input), and recommending control actions (system output), the FDMP can be utilised to support decision-making in an automatic manner, using numerical traffic data and incident information from field observation. Basically, the recommended control actions are the strength of VMS message or the ramp metering rate at each interval in a time-series manner. Note that the control approach may be shifted by the operators during the control process subjected to sustained changes in traffic trends. Likewise, the control strategy is selected on the basis of the recommended control approach and network attributes, including the volume/capacity ratio, the ramp queue, and the congestion level of diversion routes. Like the control approach, the strategy may change during the control process subjected to a sustained evolution of ramp queue and mainline traffic.

3. Formation of rules for ramp control

The above section describes the overall decision-making logic for control approaches and control strategies. Given the selected control strategy, the system starts the operation at the implementation level. The ramp traffic control for expressway congestion management targets the following primary objectives [9,39]:

- Minimize mainline congestion
- Maximize throughput
- Minimize the total travel time (TTT) and total time spent (TTS) in the network.

Subjected to constraints:

- Prevent excessive ramp queues
- Prevent secondary queues at ramp merges
- Prevent severe congestion on the alternative routes.

It is possible that the above objectives are conflicting and constraints cannot be satisfied simultaneously. For example, the objective to minimize mainline congestion requires restrictive metering rates that induces formation of ramp queues, which may result in an increase in TTS in the network. The constraint to prevent a secondary queue produces minimal metering rates during heavy local congestion, and this conflicts with the constraint to reduce ramp queues [39]. Therefore, in defining and tuning the fuzzy rules, a reasonable balance between control objectives should be maintained, and the constraints be observed.

To allow better observation and tuning of the parameters, in the following section the process of rule formation is presented with focus on the local ramp control. Control actions for local ramp control are essentially the determination of the ramp flow that should be released to enter the mainline in each time interval. Essentially, the ramp flow is calculated using the ramp metering rate, indicated as a percentage of the metering ramp capacity. The formation of rules is conducted toward a specific measurable objective, or to balance between objectives.

3.1 Input variables

Fig. 9 illustrates a layout of an expressway section for local ramp control that includes an on-ramp, upstream and downstream ramp segments. A lane-closure incident is assumed to occur downstream of the ramp. The inputs for determining the ramp flow include the traffic congestion level upstream of the incident location (downstream of the ramp), the traffic demand upstream of the ramp, the ramp queue, and other incident attributes.

Traffic congestion level upstream of the incident location

As explained earlier, the traffic congestion level upstream of the incident location (downstream of the ramp) is evaluated using speed and density variables obtained from the traffic surveillance system. The congestion level is classified into 5 predicates:

$$CL = \{FreeFlow,\ Light, Moderate, Heavy, VeryHeavy\} \tag{7}$$

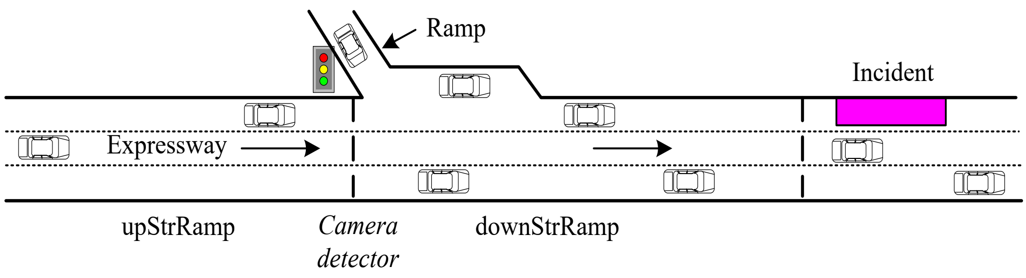

Fig. 9. Layout of local ramp control

If the congestion level of the mainline traffic is low or light, the level of ramp flow will be high. By contrast, if the congestion level of the mainline traffic is heavy or very heavy, the level of ramp flow will be restricted to avoid mainline congestion.

Volume/Capacity ratio

The volume/capacity ratio of the mainline upstream of the ramp is an important factor in determining the ramp flow. For generality, we assume that the lane-closure incident has a remaining capacity denoted as C^*, hence the ratio indicates the relation between the demand of traffic (*V*) that wishes to transverse the expressway mainline at the ramp location and the (reduced) road capacity at the incident location. Given the V/C^* ratio, the level of the ramp traffic to be added to the expressway can be inferred. If the ratio is low, the level of ramp flow will be high. By reverse, if the ratio is high, the ramp rate should be restricted to avoid mainline congestion. The V/C^* ratio is represented by four fuzzy sets (Fig. 10):

$$V/C^* = \{Low, Medium, High, Very\_high\} \quad (8)$$

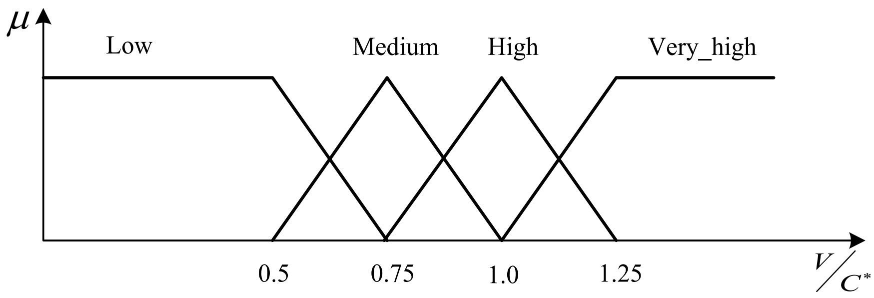

Fig. 10. Membership functions for (adjusted) V/C^* ratio

Ramp queue

The queues on ramps can be observed by means of queue detectors installed at the check-in point and at the ramp entrance. The magnitude of queues on the ramps exhibits high demand of street traffic that wishes to enter the expressway. Prevention of excessive ramp queues is one of the primary objectives of congestion management. Maintaining reasonable ramp queues is important since it is difficult to dissipate the queues without causing mainline congestion if the queues are too long. With respect to social equity, although preventing excessive ramp queue does not always improve system-wide TTS, it helps avoid ramp traffic facing overly long delays.

For classification of the concept *ramp queue,* engineering judgments are required. Fig. 11 illustrates a template membership functions for ramp queue, classified into three fuzzy sets *short*, *medium*, and *long* queue in association with the percentage of the maximum physical ramp storage $Q_{R-\max}$.

$$Q_R = \{Short, Medium, Long\} \quad (9)$$

It is worth noting that the parameters of membership functions for ramp queue are site-specific since the queue management strategy aims not only to prevent excessive queue, but also to minimize the system-wide TTS. Therefore, the control points (a, b, c) of the fuzzy partition should be calibrated through a sensitivity analysis. Given a network (mainline, ramp) and a control system, the values of control points are altered while the network geometries are kept unchanged. The system is run in different iterations to observe how the objective function (e.g: TTT, or TTS) change with the values. The values should be such that as to optimise the objective function.

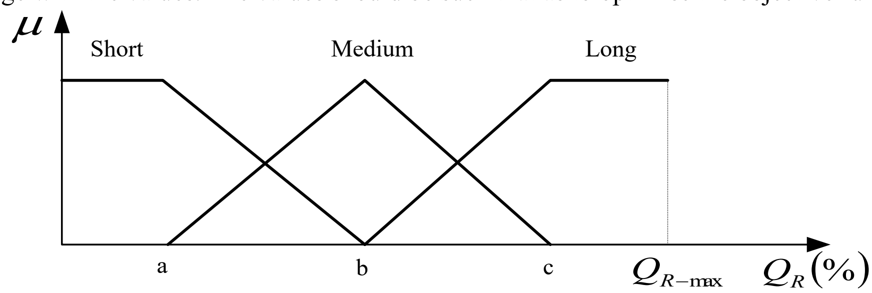

Fig. 11. Membership functions for ramp queue

Other input variables

In addition to the three aforementioned input variables, the FDMP may consider other incident attributes as complementary factors to see whether the local control strategy being implemented is adequate, or a corridor control should be adopted. The factor of interest may be the remaining time, being the duration from the current time to the expected end time of the incident. Although the predicted incident duration is a random variable and is hard to obtain precisely, it could be reasonable to estimate it by the traffic operator or by incident response team in considering incident attributes (incident type, incident severity, expected response time), the time of day, and the background traffic.

3.2 Output variable

The output of the FDMP (MS-FLC) for the local ramp control is the flow rate of the ramp traffic that is allowed to enter the expressway in each time interval. For generality, the ramp flow rates are indicated by the relative ratio between the ramp flow *(V_R)* and of the ramp flow ramp metering capacity (C_R), $\left({V_R}/{C_R}\right)$, which encompasses from *very low* to *very high* levels (Fig. 12).

Ramp_Flow = {Very_low, Low, Medium, High, Very_high} (10)

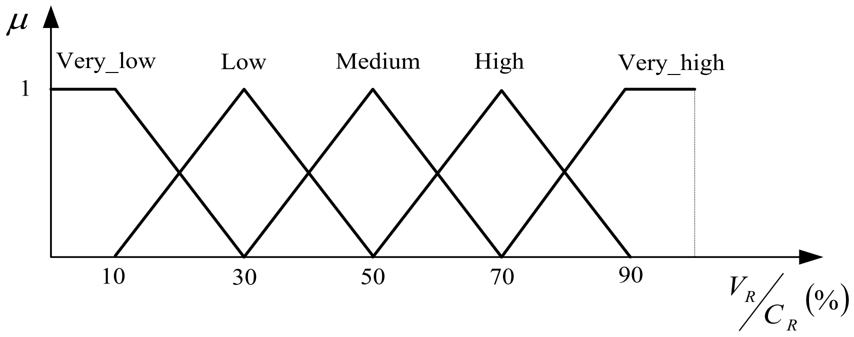

Fig. 12. Membership functions for ramp flow

To obtain a single numerical value for the ramp flow, the recommended ramp flow is obtained by defuzzifying the control output that is represented by several fuzzy values.

3.3 Rule formation for control actions

With the stated sets of state and control variables, the input-output rule mapping can be conducted using traffic engineering knowledge. The formation of rules is conducted such that the principal objectives and constraints of the control strategy - the amelioration of the mainline congestion and prevention of excessive ramp queues - are observed. Since these two objectives are often conflicting to each other, rules should be designed to compromise them at a balance point.

This section explains the formation of rules for control actions with focus on local control. The local control primarily handles the situations that are associated with slight and moderate intervention levels, while the corridor-wide control manages the situations that are associated with strong and very strong intervention levels (see Fig. 6) However, without loss of generality under the fuzzy logic concept, we propose that the local control can be extended to a lower level of heavy congestion. In the stated broader research project (MS-FLC), we introduced a concept known as "*congestion status"* that quantifies the spatial magnitude of the congestion being considered given the number of vehicles in queue that forms as demand exceeds available capacity. It is probable that queues only form under heavily congested situations, thus the MS-FLC evaluates the status of congestion based upon the queue length under the heavy congestion category. Fig. 13 plots membership functions for queue length on expressways.

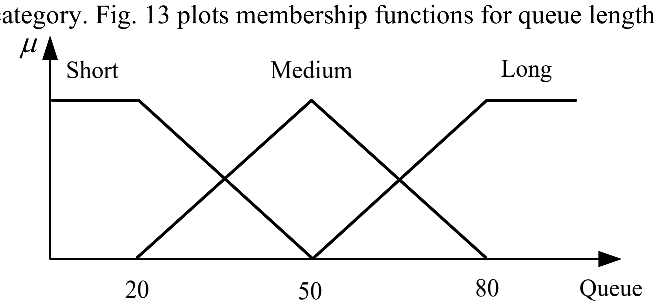

Fig. 13. Linguistic values of queue length

The linguistic values of the queue length variable are set as:

$$Queue = \{Short, Medium, Long\} \quad (11)$$

and linguistic values for the congestion status are set as (Fig. 14):

$$C\_Stat = \{SQ - HC, MQ - HC, LQ - HC\} \quad (12)$$

The abbreviations stand for *short queue – heavy congestion, medium queue – heavy congestion,* and *long queue – heavy congestion*, respectively.

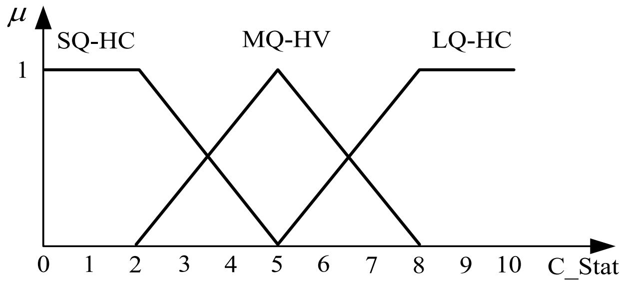

Fig. 14. Fuzzy sets of congestion status

The parameters of membership functions of the queue length should primarily be learnt from traffic control practice, whereas the partitioning of the domain of congestion status may be made using grid clustering. It should be noted that although the term *queue* is associated with heavy congestion, it does not necessarily imply the standstill traffic. Rather, it refers to slow-moving traffic streams. As an example, the queue configuration set for average spacing is between 10 and 20 m, and for speed range between 5-10 km/h [44].

Table 2 summarizes the decision table for rules with the local ramp control strategy that includes 24 rules. The rule base considers the free-flow, light and moderate congestion, and short queue – heavy congestion (SQ-HC) situation. Each rule is a mapping between two (three) predicates in the rule conditions and one predicate in the rule conclusion. The rule conditions are joined with *AND* connectives. Under some specific favourable mainline conditions (rules 1, 2, 7, 8, 13, 14) and critical mainline congestion (rules 6, 12, 18, 23, 24) the rule are triggered without considering the ramp queue. In correspondence to the control objectives, the conditions of the rules consider the traffic condition (congestion level, CL) upstream of the incident *(downstream of the ramp)*, the traffic demand (indicated by the V/C^* ratio) *upstream of the ramp*, and the ramp queue (see Fig. 12). The rule conclusion reflects the control action that infers ramp flow based upon the rule conditions in the direction of the key control objective that elaborates the control goals. For scenarios such that the traffic condition upstream of the incident and the V/C^* upstream of the ramp favour high ramp flows, the rules can be generated regardless of the ramp queue status. For example, a number of rules (rules 1, 2, 6, 7, 8, etc.) in Table 2 consider only two inputs: if the predicted CL *downstream* of the ramp is *Free-flow* (or *Light*), and the demand (V/C^*) *upstream* of the ramp is *Low*, then most of the ramp demand should be released.

Examples of rules:

R1: If CL is Free_flow and V/C^* *is Low then Ramp_Flow is Very_high*

R2: If CL is Free_flow and V/C^* *is Medium then Ramp_Flow is High*

Table 2. Decision table for rules with local ramp control

Rule	Rule condition			Rule conclusion	Key Control objective
	Congestion level upstr. of the incident	V/C^* upstr. of the ramp	Ramp Queue	Ramp Flow	
1	Free-flow	Low	--------	Very_high	Maximize mainline utilization
2	Free-flow	Medium	--------	High	Maximize mainline utilization

3	Free-flow	High	Short	Low	Prevent mainline congestion
4	Free-flow	High	Medium	Medium	Maintain acceptable ramp queue
5	Free-flow	High	Long	High	Prevent excessive ramp queue
6	Free-flow	Very_high	--------	Low	Prevent mainline congestion
7	Light	Low	--------	High	Maximize mainline utilization
8	Light	Medium	--------	Medium	Balance between objectives
9	Light	High	Short	Low	Prevent mainline congestion
10	Light	High	Medium	Medium	Prevent mainline congestion
11	Light	High	Long	Medium	Prevent excessive ramp queue
12	Light	Very_high	--------	Very_low	Prevent secondary queue
13	Moderate	Low	--------	Medium	Balance between objectives
14	Moderate	Medium	--------	Medium	Balance between objectives
15	Moderate	High	Short	Low	Prevent secondary queue
16	Moderate	High	Medium	Low	Prevent secondary queue
17	Moderate	High	Long	Medium	Prevent secondary queue
18	Moderate	Very_high	--------	Very_low	Prevent mainline congestion
19	SQ-HC	Low	--------	Medium	Balance between objectives
20	SQ-HC	Medium	Short	Low	Prevent mainline congestion
21	SQ-HC	Medium	Medium	Medium	Prevent excessive ramp queue
22	SQ-HC	Medium	Long	Medium	Prevent excessive ramp queue
23	SQ-HC	High	--------	Low	Prevent mainline congestion
24	SQ-HC	Very_high	--------	Very_low	Prevent mainline congestion

The inputs are combined in such a way that predicates are scaled gradually over the input domains, and the outputs are translated elegantly from one fuzzy value to another. For example, in the following rules the V/C^* changes gradually from *Low* to *High,* whereas the *Ramp_Flow* is set from *High* to *Low*.

R7: If CL is Light and V/C^* *is Low then Ramp_Flow is High*

R8: If CL is Light and V/C^* *is Medium then Ramp_Flow is Medium*

R9: If CL is Light and V/C^* *is High and Ramp Queue is short then Ramp_Flow is Low.*

Nevertheless, there are cases where different inputs produce the same output. For example, rules 13 and 14 propose a *Medium* level of ramp flow associated with different levels of traffic demand V/C^* *:*

R13: If CL is Moderate and V/C^* *is Low then Ramp_Flow is Medium*

R14: If CL is Moderate and V/C^* *is Medium then Ramp_Flow is Medium*

The rules regulate the ramp rate subjected to the demand upstream of the ramp $\left(V/C^*\right)$ so as to prevent the mainline congestion:

R6: If CL is Free-Flow and V/C^* *is Very_high then Ramp_Flow is Low*

or to prevent a secondary congestion at the ramp metering point:

R12: If CL is Light and V/C^* *is Very_high then Ramp_Flow is Very_low*

R15: If CL is Moderate and V/C^* *is High and Ramp_queue is Short then Ramp_Flow is Low.*

The reason for this restriction is that when the mainline is congested, the ramp traffic will hardly find an acceptable gap to join the mainline, so a secondary queue of the metered vehicles may form spontaneously. If a secondary queue persists, ramp metering is not beneficial. At the extreme, vehicles in the secondary queue may try to encroach upon the mainline, breaking down traffic upstream of the ramp and creating safety risk. Therefore, in the presence of a secondary queue, it is imperative that the vehicles be stored on the ramp to wait for an opportunity in the next period rather than being metered.

In addition to traffic upstream of the incident and V/C^* ratio, the ramp-queuing status needs to be considered. The rules are designed to achieve a proper balance between alleviating mainline congestion and adjusting the queue length. For example, with the same level of traffic demand upstream, the ramp flow is set to less restrictive rates if the ramp queue develops:

R3: If CL is Free-Flow and V/C^* *is High and Ramp_queue is Short then Ramp_Flow is Low*

R4: If CL is Free-Flow and V/C^* *is High and Ramp_queue is Medium then Ramp_Flow is Medium*

R5: If CL is Free-Flow and V/C^* *is High and Ramp_queue is Long then Ramp_Flow is High.*

Most of the rules aim at a certain principal objective that could be set by the control operator or traffic manager. The objectives are the elaboration of overall goals of ramp control. If the traffic condition upstream of the incident is *Free-flow* or *Light* and traffic demand is *Low/Medium*, the ramp flow is set to *High/Very_high* level so as to *maximize mainline utilization* (rules 1, 2, 7). In contrast, if the traffic demand $\left(V/C^*\right)$ ratio upstream is *High/Very_high* the ramp flow is set to *Low/Very_low* levels to *prevent mainline congestion* (rules 3, 6, 9, 10, 18, 20, 23, 24). In addition, the ramp flow is adjusted according to the ramp queue status so as to *maintain acceptable ramp queue* (rule 4), to *prevent excessive ramp queue* (rules 5, 11, 21, 22), or to *maintain a balance between objectives* (rules 8, 13, 14, 19). Finally, if the traffic on the mainline is congested, the restriction of the ramp flow is to target *preventing a secondary ramp queue* at the ramp bottleneck (rules 12, 15, 16, 17). The reason for this restriction is that when the mainline is congested, the ramp traffic will hardly find an acceptable gap to join the mainline, so a secondary queue of the metered vehicles may form spontaneously. If a secondary queue persists, ramp metering is not beneficial but may cause traffic breakdown on the mainline.

Fig. 15 illustrates an example of the FIS interface of the rule base for ramp control with the set of 24 rules presented in Table 2. The assumed inputs include the predicted congestion level upstream of the incident (predicted-CL) = 2.97, the V/C^* upstr. of the ramp (Vd-C ratio) = 0.575, the ramp queue (Qramp) = 30, and the congestion status (Con-Status) = 3.23. For the given data inputs, most of the rules are active, while rules 15, 17, and 18 are inactive since none of the predicates in the rule conditions is satisfied. Being connected with *AND* operator, the membership values of the rules are calculated using *MIN* operation.

$$\mu_{A\cap B}(x) = MIN(\mu_A(x), \mu_B(x)) \tag{13}$$

For example, rule 8 defines:

If Predicted CL is Light and V/C^* *is Medium then Ramp_Flow is Medium*

For the given inputs, the output of rule 8 is inferred as:

$$\mu_{Medium}(Rampflow) = \min\left[\mu_{Light}(CL = 2.97), \mu_{Medium}\left(V/C^*\right) = 0.575\right] = \min[0.83, 0.33] = 0.33 \tag{14}$$

The FIS uses the MAX aggregation method that defines the union of fuzzy sets to obtain the aggregated output. The union can be generalized for n fuzzy sets over the same universe of discourse:

$$\mu_{\cup}(x) = \mu_1(x) \cup \mu_2(x) \cup \ldots \cup \mu_n(x) \tag{15}$$

and the centroid defuzzification (COA) to obtain the final script value of the outputs. The COA finds the central point of specific regions such as the overall aggregated output or the centre of the largest area. The method computes the crisp value as:

$$y' = \frac{\int_S y\mu(y)dy}{\int_S \mu(y)dy} \tag{16}$$

where S is the support of $\mu(y)$.

The final output of ramp flow is 61.8%, namely $0.618 \times C_R$. For example, if the ramp metering capacity (C_R) is 800 veh/h, the ramp metering flow will be approximately 495 veh/h. Given the recommended ramp flow, the green time in each signal cycle can be inferred.

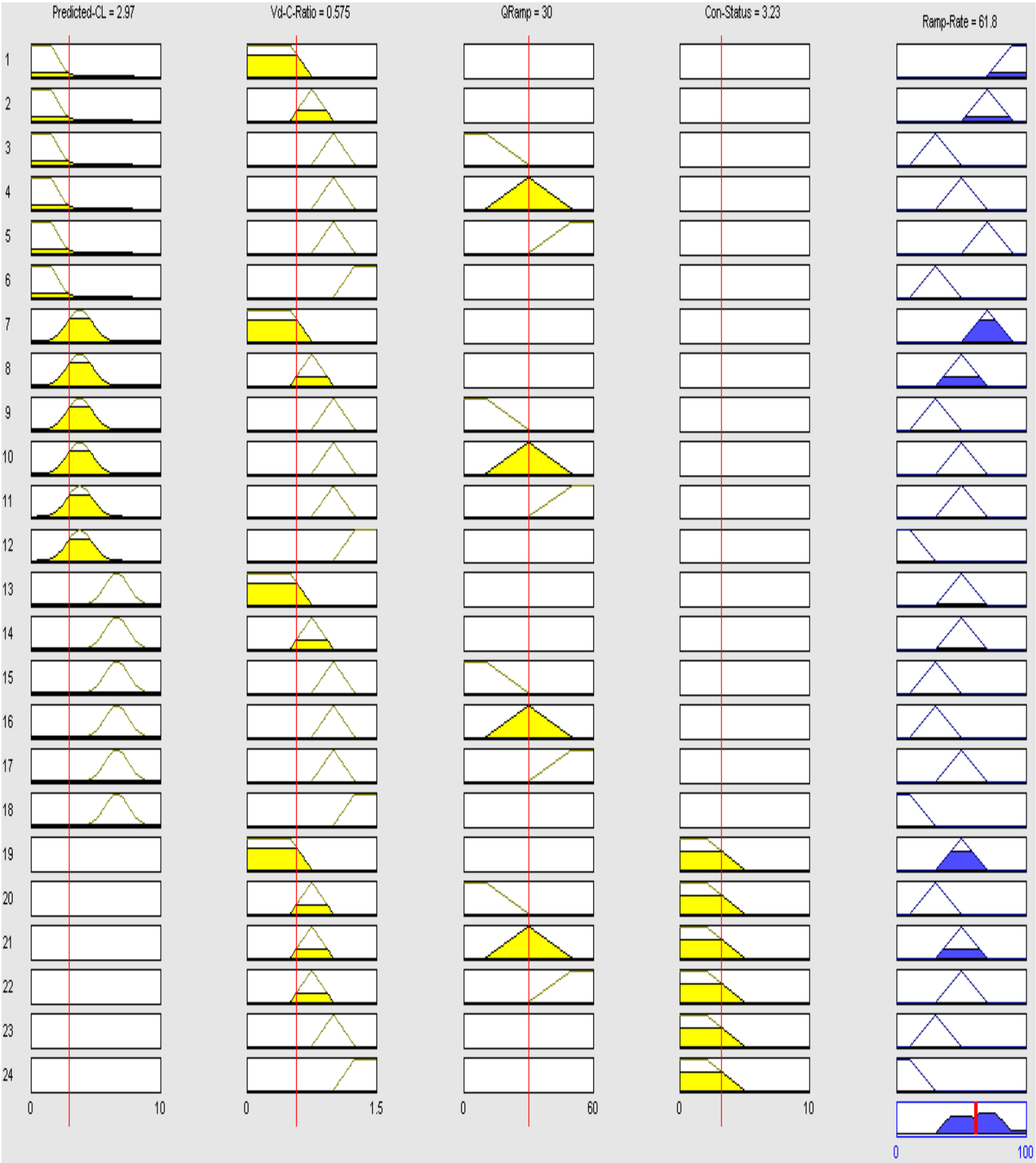

Fig. 15. FIS for ramp control using MIN implication method

4. Extension: validation and evaluation of the MS-FLC

As stated in the “Introduction”, in the broader research project [12], we have developed a multi-stage fuzzy logic controller (MS-FLC) for traffic control for congestion management on expressways. The decision-making process for traffic control for congestion management on expressways using the MS-FLC consists of three tasks: (1) evaluation of current traffic congestion; (2) prediction of traffic congestion tendency; and (3) recommendation of control strategies and control actions to alleviate congestion. For the MS-FLC validation and evaluation, a traffic simulator controller (TSC) that consists of a car-following model (CFM) [45] and a traffic controller (TC) was developed (Fig. 16). By including the CFM component in the model, the dynamic longitudinal interactions between vehicles, namely car-following behaviors, are replicated. The TC receives the aggregated outputs for traffic control purposes.

The TSC model was developed in SIMULINK in MATLAB. It functions more like a macroscopic traffic simulation model since only aggregated traffic variables, which are the parameters of interest, are generated. The traffic on the multi-lane expressway where the data was collected is represented as an equivalent single-lane system for model calibration and validation. The MS-FLC is embedded in the TSC and is evaluated across several incident scenarios by comparing its performance with ALINEA\Q, a popular local ramp control algorithm.

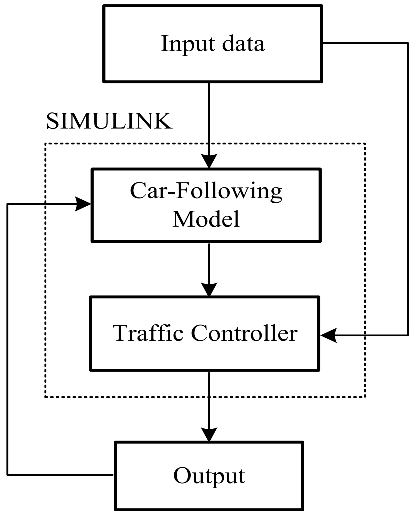

Fig. 16. Conceptual model of the TSC

Three control methods were considered: No control; ALINEA\Q control, and MS-FLC control. ALINEA is the most widely used technique in the close-loop control [46], and is an efficient local-ramp control algorithm for monitoring the mainline traffic. ALINEA determines the metering rates such that the traffic state on the expressway approaches a pre-defined condition. Developed as an enhancement of ALINEA, the ALINEA\Q [18] incorporates ramp control with ramp queue management that maintains the ramp queue within a desirable queue length.

The key measures of effectiveness (MOEs) include total travel time (TTT), total waiting time (TWT), total time spent (TTS), mean density (MD), maximum length of queues on the expressway (max Q_exp), and maximum length of queues on the ramp (max Q_ramp), and the average speed (MS). The experiment cases considered various cases associating with different levels of ramp demand, capacity reduction and incident location, while the mainline demand were maintained in the range 1,000-1,100 veh/h/lane.

Through the evaluation in comparison with the No-control scenario and ALINEA (ALINEA\Q) ramp control algorithm, it showed that the MS-FLC model significantly outperformed ALINEA\Q with respect to global objectives, significantly improved mainline travel conditions, and substantially reduced ramp queues. Particularly, under high traffic demand and severe capacity reduction, the MS-FLC brought higher travel time savings as well as improvements of traffic conditions on both the mainline and ramp. Not only does the MS-FLC outperformed ALINEA\Q in managing ramp traffic, it also outperformed ALINEA\Q in managing the mainline flow under critical incident congestion. Details on the MS-FLC model validation and evaluation can be seen in [12] and [45].

To explore the effects of changes in these parameters on the comparative performance of the control approaches and to enhance confidence in the models’ performance in an uncertain environment, a sensitivity analysis was conducted. The simulation parameters include changes in the network length and ramp storage capacity. It was found that the superiorities of the MS-FLC control method over “No control” deteriorate as the network length increases, and increase as the ramp storage capacity increases.

5. Discussions

The FDMP for traffic control in expressway congestion management presented in this paper is the last (3rd) stage of the MS-FLC. The stage receives the current traffic data from stage 1 and short-term predicted traffic data from stage 2 to recommend control strategies and control actions. Strategies associating with these two types of data are known as *reactive control* and *proactive control*, respectively. Since there is a time lag from data collection and analysis to control implementation, reactive control may react to lagged traffic data and information. By the time the decision is made, the prevailing traffic states may have already changed and new problems have arisen, leading to a decline in efficiency of recommended solutions. The proactive control, on the other hand, reacts to near-term anticipated conditions that are more relevant to the prevailing conditions. From the control perspective, the anticipated information allows sufficient time envelops for setting or resetting control parameters. For these reasons, proactive control is more theoretically attractive than reactive control [47]. Nevertheless, the benefits of proactive control may not be fully realized due to potential inaccuracies of traffic prediction. In these regards, the two control strategies should be complementarily implemented. Reactive strategy can be used for setting control parameters under critical situations such as incident congestion, excessive queues, over-saturation, or for adapting to changes in the incident events. Proactive control, on the other hand, should be the primary mode of operation during the whole control process, especially when traffic conditions are not yet critical.

Unlike the automatic control that attempts to "optimize" mathematical objective functions such as the total travel time or total time spent in the system, the rules in the FDMP are empirically defined based on engineering judgements, so only sub-optimal solutions are obtained. In contrast, the FDMP is more flexible since it allows combination of both the computer processing power and human expertise: based upon the FDMP's numerical outputs and its recommend solutions, the human operator carries out further judgements and reasoning to make decisions. This operational manner fits the rule-of thumb that the DSS's function is to support human's decision-making, but not to take over the operator to make decisions. That is particularly true for strategic decisions that require further consideration of available supply/demand factors and practical observation to determine control strategies, apart from the FDMP's recommendations. For control rules at the operational level, the operator does not need to make decision every time, but can rely on the FDMP's established operational procedure.

It is worth noting that the rules are designed in an incremental manner, so the outputs are translated elegantly from one rule to another. From the engineering standpoint, this creates an operational advantage since the traffic operator does not need to baby-sit the control by continual adjustment of the metering rates. The rule-based design allows the fuzzy controller to perform well under a wide range of conditions. The FDMP design is oriented toward congestion management, and it could be applied to both recurring and non-recurring congestion, since the problem-solving strategy for both types of congestion aims at demand-capacity balance on the mainline and the ramp. Issues such as capacity reduction and queue management have been addressed, and the rule base of the FDMP can be further customised with incident attributes such as incident type, incident duration, number of lane closure, etc., given the flexibility of the fuzzy logic systems.

Extension: The rule formation for control actions presented in this paper is basically for local ramp control. Although the local control accounts for most applications, the corridor-wide control requires coordination of controllers along the expressway corridor. Since most of the traffic monitoring and control routines for an expressway network are implemented at the Traffic Management Centre (TMC), the MS-FLC architecture should be designed to assist TMC personnel in corridor-wide control.

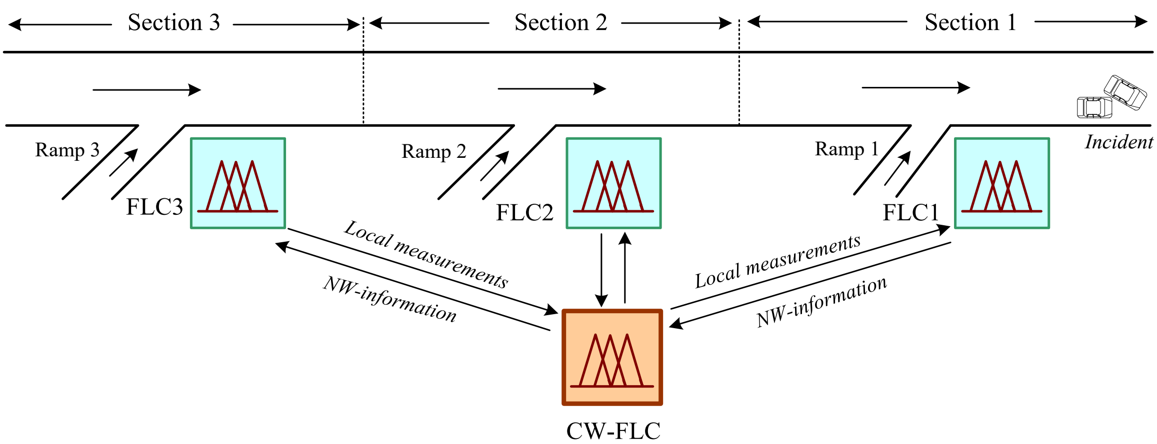

Fig. 17. Proposed architecture of corridor-wide CW-FLC

Fig. 17 illustrates the proposed architecture of the MS-FLC for a typical corridor-wide control, with assumed critical incident conditions. An expressway corridor is divided into N sections, each of which has a local FLC to manage traffic at the corresponding section. The local FLCs have their own rule bases, while the corridor-wide fuzzy logic controller (CW-FLC), known as the coordinator, contains specific rules to govern the coordination between FLCs with corridor-wide default control parameters.

In normal conditions the FLCs work independently of the CW-FLC. Under special conditions, the FLC immediate downstream and the FLCs upstream of the incident form a control group, which is taken over by the CW-FLC with coordinated rules activated. The immediate downstream FLC is used to encourage the utilisation of available capacity downstream of the incident, while the immediate upstream FLC is the prime controller that has the most direct and primary impacts to the control scheme. In principle, each local FLC issues control actions based on the measurements on its upstream and downstream segments but adjusted to control directives from the CW-FLC, which passes corridor information on individual segments, and receives the local measurements as well as control actions from individual FLCs. The rule base of the CW-FLC involves mechanisms that make coherent integration between rules in the local FLCs. In case conflicts or incoherence between FLCs exist, the CW-FLC coordinator resolves the problems by setting priorities over local FLCs.

6. Conclusions

This paper presents the 3rd stage of the MS-FLC that develops a fuzzy-based decision-making procedure (FDMP) for traffic control strategies and control actions. The FDMP consists of three blocks: intervention level, control strategy, and control action. Given this reasoning process, the FDMP's rules pertain to both strategic level and operational level. While the rules at strategic level (control approach and control strategy) are methodologically recommended for all types of control, rules at operational level focus on local ramp control to facilitate tuning of the rule base design. The results from this research allow the following conclusions to be drawn:

- The FDMP represents a comprehensive procedure in deriving control strategies and control actions. The FDMP rule base is designed to recommend solutions at both strategic and operational levels.
- FDMP control actions are derived from a systematic decision-making logic that is established based upon current and anticipated traffic data and incident information. Rule base design is consistently oriented toward achieving desirable control objectives in order to provide structured and consistent control actions.
- The FDMP targets a balanced congestion management between the mainline and the ramp using compromise rules, thus the ability to handle a broad range of conditions is improved.
- The FDMP facilitates using various forms of available traffic and incident data to derive control actions, making the system-wide gains possible, and providing potential extension to corridor-wide management.
- The model's flexibility: the FDMP could be applicable to both the recurring and non-recurring congestion, since the problem-solving strategy for both types of congestion aims at demand-capacity balance.

Meanwhile, several shortcomings should be noted, including: (i) following fuzzy logic approach, FDMP is a highly non-linear system with complex stability behavior, but there exists not yet a systematic methodology for the model stability analysis; (ii) the FDMP employs a considerable number of input parameters, thus extensive observations and measurements from the network are required, even though data analytics shall become ever quicker with the rapid pace in computing developments, and (iii) there are no clear cuts between the fuzzy terms such as low, medium, and high demands. The terms are primarily empirically defined based on engineering judgements and expertise, but not verified numerically.

Since this paper covers only a part of a larger research project, the ultimate numerical result of the system is not readily available. Given the limited space, there are a considerable number of points that could not be elaborated in detail, but only methodological framework is presented. The significance of this paper, to a great extent, can be focused on engineering judgements within the context of the wider research scope. Since FDMP (the 3rd stage) acts as a crucial link of the MS-FLC, the merit of this paper can further be linked to [12] that validates and evaluates the performance of MS-FLC in its application.

Future research may focus on development of a rule base of the CW-FLC coordinator that monitors the operation of the whole FLC control group. In addition, research on ATMS-ATIS system integration between ramp control and route control following fuzzy logic approach is also of value-add.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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