CHANGEOVER FROM DECISION TREE APPROACH TO FUZZY LOGIC APPROACH WITHIN HIGHWAY MANAGEMENT

*J. Kuklová**, *O. Přibyl**

Abstract: This paper deals with the changeover from the decision tree (bivalent logic) approach to the fuzzy logic approach to highway traffic control, particularly to variable speed limit displays. The usage of existing knowledge from decision tree control is one of the most suitable methods for identification of the new fuzzy model. However, such method introduces several difficulties. These difficulties are described and possible measures are proposed. Several fuzzy logic algorithms were developed and tested by a microsimulation model. The results are presented and the finest algorithm is recommended for testing on the Prague City Ring Road in real conditions. This paper provides a guidance for researchers and practitioners dealing with similar problem formulation.

Key words: *highway management, fuzzy logic, traffic control, speed harmonization, variable speed limits*

Received: July 27, 2015
Revised and accepted: January 20, 2017

DOI: 10.14311/NNW.2017.27.008

1. Introduction

Highway management is a strategic approach seeking to maximize driver satisfaction and road safety. It is a current topic in our society, since the existing infrastructure has become insufficient and unsafe due to increasing traffic demand. Such a problem can be carried out in two possible manners. Highway widening is the more intuitive solution. In the positive side, it results in certainly increased capacity and higher possible speeds. On the other side, the widening means temporary highway closure and high overall costs. Thus, building of new infrastructure is not always a suitable solution and the current efforts are directed towards finding an appropriate management strategy using Intelligent Transport Systems (ITS). It has been proven that a suitable impact to traffic flow enables the increase of highway capacity even without the need to build new infrastructure [17]. The installation of Variable Message Signs (VMS) along a highway brings a wide range of possibilities which consist of transmitting information to the driver by means of informational messages, and warning, mandatory or restrictive signs.

---

[*] Jana Kuklová; Ondřej Přibyl – Corresponding author; Department of Applied Mathematics, Faculty of Transportation Sciences, CTU in Prague, Na Florenci 25, CZ-110 00 Praha 1, Czech Republic, E-mail: `kuklojan@fd.cvut.cz`, `pribylo@fd.cvut.cz`

Speed harmonization is one of the key highway management strategies addressing the regular congestions nascent in the peak periods. Depending on the actual traffic flow parameters, Variable Speed Limits (VSL) are displayed on VMS. Such impact to traffic flow results in reduced average speeds, reduced speed variation, improved lane utilization, and a calmer driving experience [1, 12]. The traffic flow then becomes smoother, the probability of a severe traffic accident is lower and the highway efficiency increases. In addition, VSL brings certain environmental benefits such as decreased emissions and noise.

In the event of the introduction of a VSL system, the policy and rules for displaying the speed limits must be defined. For this purpose, the approach using decision trees is the most frequently applied and documented. One or more traffic flow parameters are selected and thresholds for VSL displaying are defined. In most systems, the traffic flow parameters are complemented by the parameters representing weather conditions. The VSL systems deployed in the United Kingdom [7] and the Netherlands [18] utilize flow intensity (veh/h) and average flow speed (km/h) as input variables. The system MARZ, described in German standards, utilizes local density (veh/km) in addition to the two mentioned variables [3]. References [3, 7, 18] also treat the so called hysteresis contributing to the reduction in the amount of VSL switching. This phenomenon arises from the nature of traffic flow where fluctuations are present even when this is stable. Hysteresis is partially solved by data pre-processing. Moreover, different thresholds or different decision trees for VSL increase and decrease are used.

More recent VSL systems increase the number of aforementioned input variables by standard deviation of speed distribution [6, 10]. Other systems use occupancy (%) instead of local density [1]. Actually, in [8], occupancy is presented as the most stable variable. Hence, it is used as the major indicator for VSL. More sophisticated algorithms also consider the traffic flow parameters in adjacent sections [3, 9]. Other systems only perform synchronization of resulting speed limits in adjacent sections, e.g. [8].

Direct improvement of the system MARZ is achieved by the introduction of an objective function [20]. Such objective function considers lost time, probability of an accident, and average speeds among other variables. Further enhancement of simple rule-based algorithms can be achieved by introducing fuzzy logic. Fuzzy set theory was first introduced by L.A. Zadeh [22]. Since then, it has found application in many control systems including highway control systems [16].

It has been proven that fuzzy logic is successful in problems where exact mathematical modelling is hard to use but an experienced human operator can control the process [15]. It thoroughly fits the speed harmonization problem, which is demonstrated for instance in the Dutch project [18]. Before the automation of highway control, the traffic flow was controlled manually by human operators based on their experience. Moreover, the automation process arises from expert knowledge. Fuzzy logic has found employment in the issue of on-ramp metering whereas most projects deal with speed harmonization together with on-ramp metering, e.g. [4, 21], which is beyond the scope of this paper.

An independent speed harmonization algorithm applying fuzzy logic was developed and tested within a project of the Federal Highway Administration in the USA [13, 14]. In total, seven input variables are defined. It is apparent that the more input variables the control system uses, the more complex the fuzzy inference mechanism becomes. The problem of the so-called curse of dimensionality is described, for example, in [2]. The complexity of the system can be significantly reduced by a multi-level fuzzy control algorithm as proposed in [21]. The authors designed a three level algorithm emphasizing the architecture ability to be extended and/or modified.

In the Czech Republic, an automatic highway management system has been developed. The system consists of different strategies which are realized by means of VMSs. Since the system has a modular architecture, different strategies can be developed and introduced separately (a priority level is then assigned to each strategy). This paper is focused on the strategy of speed harmonization which is used to achieve more uniform and stable traffic flow and to facilitate recovery from congestion by reducing speed limits. Actually, it deals with the policy of VSLs activation based on traffic flow parameters.

Speed harmonization systems in the Czech Republic can be split into three distinct generations. Each generation represents one approach to the policy of VSL displaying: (1) decision trees, (2) fuzzy logic, and (3) multi-agent systems. Each generation is in a different phase of implementation. Decision tree algorithm is fully developed and has been in place since 2010. New fuzzy-logic algorithms have been developed and are currently in the process of evaluation. Multi-agent systems are in the early stages and form a new research trend [11].

The prime fuzzy-logic algorithms developed in the Czech Republic came from direct changeover from decision trees to fuzzy logic. It was believed that the expert knowledge introduced in decision trees would be carried forward to the new approach, while further introducing the advantages of a fuzzy approach. The aim of this paper is to document the mentioned changeover and present the improvement of the control algorithm on the background of the results from microsimulations.

This introductory section is followed by the methodological section where the implemented decision tree algorithm is introduced and the changeover between decision trees (bivalent logic) and fuzzy logic is thoroughly described. First, the overall architecture of the new fuzzy logic system is presented as a follow-up to the decision tree system. Similarly, data pre-processing, fuzzification, fuzzy inference mechanism, defuzzification and speed limit assignment are described step by step. As the research revealed that hysteresis could not be directly carried forward to the new fuzzy system, it is treated separately. Finally, the fuzzy logic algorithms are evaluated based on the results from microsimulations.

2. Methodology

A decision tree algorithm for highway control by VSL was developed within the INEP project (hereafter the INEP algorithm) [5]. The algorithm was primarily designed for Czech highways with respect to its geometric design and drivers' behavior. Several thresholds were defined for three input variables. The stable traffic flow is controlled by traffic flow intensity. The unstable traffic flow is then controlled by local density and the average speed of traffic flow. The most important is the state of transition between stable and unstable traffic flow, where all three aforementioned parameters are considered. The thresholds were set during a continuous process based on results from existing projects, historical data, experience of traffic engineers and fine tuning with the use of microsimulation tools.

Hysteresis is addressed by the threshold shift between the VSL switch on and switch off conditions. Additionally, three-minute data aggregations are used. These aggregations are consequently smoothed by the average of the last three samples.

Moreover, the Road and Motorway Directorate (RMD) of the Czech Republic issued several regulations that must be followed when designing an algorithm for displaying VSL. There are four pre-defined VSL: 60 km/h, 80 km/h, 100 km/h, and 120 km/h. If no VSL is displayed, given by Czech legislation, the road speed limit is automatically 130 km/h. Several regulations for adjacent sections were issued by the RMD. For example, in the event of assessing 60 km/h in one section, displaying a speed limit of 100 km/h or higher in the upstream section is not permitted. Coordination of up to five subsequent sections was defined within the INEP project.

There are several reasons for the changeover from the decision tree approach to the fuzzy-based approach:

- Getting rid of crisp thresholds when the speed increase of a single vehicle can change the control state.
- Ability to deal with imprecision inherent in the problem domain (e.g. the input data from sensors).
- Accommodating of prior knowledge from human operator/police controlling the process.
- The model, through its linguistic formulation, is easily understood by decision makers.

More reasons for the fuzzy approach introduction are presented in [13–15]. However, the changeover cannot be performed directly and it introduces some additional issues. For this reason, a global view on the architecture is presented first, then all critical issues are treated step-by-step emphasizing the continuity of the new fuzzy logic system with the INEP algorithm.

2.1 Architecture of the fuzzy logic system

Denoting input variables Q (intensity in veh/h), V (speed or velocity in km/h), and K (local density in veh/km), the decision rules designed in the INEP algorithm match the following logical expression

$$Q \vee (V \wedge K)\,.$$

This corresponds to the aforementioned statement that the stable traffic flow is mainly controlled by traffic flow intensity, while the unstable traffic flow is controlled by local density and the average speed of traffic flow. The structure of the control rules evokes ideas of the multi-level fuzzy logic system as proposed in [21].

Fig. 1 demonstrates the architecture of the designed fuzzy algorithm. First, measured data of all input variables Q, V, and K are fuzzified. At the first level inference mechanism, unstable traffic flow, if any, is identified from the variables V

and K. The fuzzy output of the first level inference mechanism becomes the fuzzy input of the second level and can be understood as a speed limit recommendation for the second level. It is called the auxiliary fuzzy variable. At the second level inference mechanism, the output fuzzy variable is determined based on the input variable Q and the auxiliary variable. The last step according to the architecture in Fig. 1 is defuzzification in which a speed limit proposal is calculated.

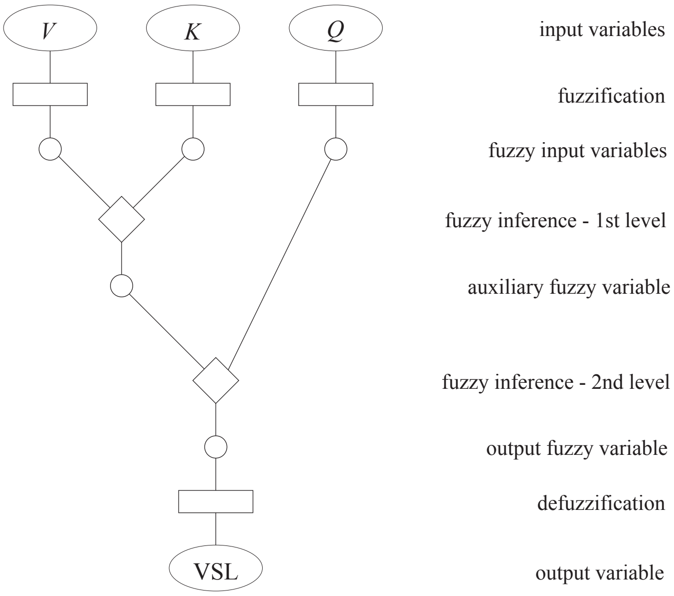


Fig. 1 *Architecture of two-level fuzzy-logic controller.*

The described architecture does not directly include data pre-processing, the final speed limit assignment and hysteresis measures, since these do not form a part of the fuzzy algorithm itself.

2.2 Data pre-processing

Even though traffic flow data are primarily aggregated in one-minute intervals, the INEP algorithm processes data aggregated in three-minute intervals. These aggregations are consequently smoothed by the moving average with the window width of three samples. On the one hand, it decreases the oscillation of the resulting speed limits and, thus, hysteresis is achieved. On the other hand, it causes a delay of up to nine minutes in response to the actual traffic. For this reason, the proposed fuzzy-logic algorithm processes data directly aggregated into the one-minute intervals and reduced window widths of the moving average were tested since it was believed that hysteresis could be achieved by other means. This is discussed in detail later in this section.

2.3 Fuzzification

Fuzzification of input data is one of the most demanding phases of the fuzzy-logic system design, especially when a variable is not either normally, nor uniformly distributed as in case of traffic data. Hence, the fuzzification requires a sound knowledge of the controlled system. Such knowledge has been embedded into the INEP algorithm by the means of the thresholds which partition the universe of each variable in several crisp intervals. The mentioned thresholds provided a basis for the determination of fuzzy linguistic variables.

The labels of linguistic variables correspond to input variables in the INEP algorithm, namely intensity, speed, and local density. The universe of each variable is given by a range of real values. For example, speed is defined on the universe of $\langle 0; 250 \rangle$ km/h. The number of fuzzy sets and the corresponding membership functions arise from the thresholds defined in the INEP algorithm. Because of hysteresis measures, these thresholds are different for speed limit switch on and switch off. Thus, the universe is divided into intervals where the speed limit is unambiguously determined, and intervals where the speed limit depends on that from the previous time interval. These intervals provided the basis for the definition of membership functions. The first mentioned intervals were converted into the cores of trapezoidal membership functions and the transitional intervals into the boundaries.

Fig. 2 illustrates how the fuzzy sets divide the universe of speed in the vertical axis and the universe of local density in the horizontal axis on the background of historical data from the controlled section.

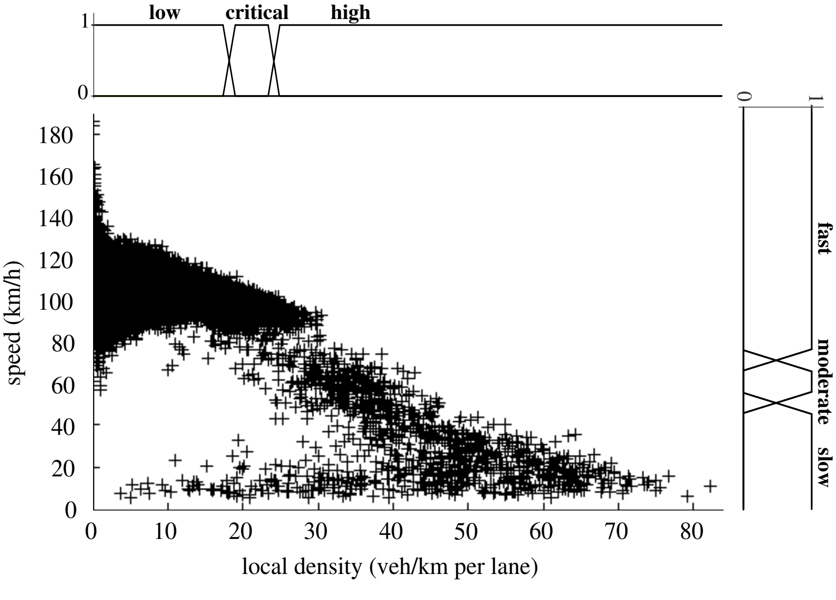


Fig. 2 *Fuzzy variable on the background of historical data.*

2.4 Fuzzy inference mechanism

Two-level architecture implies definition of two mappings from input variables onto output variable. On the one hand, this approach extends the algorithm, but on the other hand, it decreases the complexity of the inference mechanism (decreases the number of fuzzy rules) and, moreover, will enable us to introduce new variables in the future.

The Takagi-Sugeno method of fuzzy inference was selected since it enables us to define the output as a set of constants. The final output is then calculated as the weighted average of all rule inputs [19]. The output variable of the designed fuzzy algorithms is the set of constants $\{60; 80; 100; 120; 130\}$ corresponding to the speed limits in km/h given by RMD.

According to the architecture shown in Fig. 1, unstable traffic flow is identified at the first level from input variables V and K. The rules lead to the speed limits of 60 km/h or 80 km/h in case of the unstable traffic flow, otherwise, the speed limit is set to 100 km/h. Tab. I provides the survey of the rules defined at the first-level inference mechanism (e.g. IF speed IS fast AND local intensity IS NOT high THEN speed limit is 100 km/h).

First level	Local density K		
	low	*critical*	*high*
Speed V			
slow	60	60	60
moderate	80	80	80
fast	100	100	80

Tab. I *Fuzzy inference – 1st level.*

In fact, the fuzzy inference mechanism assigns to each constant from the set $\{60; 80; 100\}$ a certain value from the range $\langle 0; 1\rangle$. These values represent the memberships to the recommended speed limits. Thus, a fuzzy output of the first level is obtained. In order to introduce the auxiliary variable, three fuzzy sets called VMS_{60}, VMS_{80} and VMS_{100+} were introduced and the corresponding membership values from the first level output were assigned to the input of the second level.

VMS_{60} and VMS_{80} stand for the speed limit recommended at the first level, while VMS_{100+} means that the final speed limit will be determined at the second level based on actual traffic flow intensity. The second level inference mechanism is described in Tab. II. The rules introduced into the inference mechanisms match the rules from the INEP algorithm.

2.5 Defuzzification and speed limit assignment

The final output of the Takagi-Sugeno inference mechanism is computed as the weighted average of all rule outputs. Similarly to the first level, the rules of the fuzzy system assign to each constant from the set $\{60; 80; 100; 120; 130\}$ a certain value from the range $\langle 0; 1\rangle$. These values are then used as weights for the calculation of the final output. It means that the fuzzy algorithm output is obtained in

Second level	Auxiliary variable		
	VMS_{60}	VMS_{80}	VMS_{100+}
Intensity Q			
low	60	80	130
middle	60	80	120
high	60	80	100
limit	60	80	80

Tab. II *Fuzzy inference – 2nd level.*

the continuous range of $\langle 60; 130 \rangle$. Since the variable speed limits are pre-defined, a policy for speed limit assignment has to be established. The simplest policy assigns the nearest value of VSL from the set $\{60; 80; 100; 120; 130\}$. This policy was later changed in order to set the hysteresis (discussed in the Section 2.6).

The final speed limit assignment is always subject to the regulations for adjacent sections defined by RMD. These regulations were fully implemented in the control algorithms.

2.6 Hysteresis

Hysteresis represents the measures which decrease or even suppress the oscillation of the displayed speed limits. For this purpose, the INEP algorithm works with different thresholds for switching on and off. However, this approach is not directly transferable to fuzzy logic. It is not possible to have different rules for switching a speed limit on and off. Therefore, it is necessary to approach this issue differently. The hysteresis thus becomes the most challenging issue in the changeover.

Several methods dealing with hysteresis were developed. They are described hereinafter in this section. The methods are discussed further in the next section on the background of the results of the microsimulations.

The first method, designated "Memory" Hysteresis, defers speed limit increases using a memory. The algorithm memorizes the speed limit assigned in the previous time instant and the proposed oncoming speed limit. Furthermore, an auxiliary variable tracking the changes in speed limits is introduced. This variable enables the algorithm to reveal and suppress local oscillations using penalties. In the event that a tendency to an oscillation between two speed limits is detected, the lower speed limit is automatically assigned. A speed limit increase is performed only in case that the increase is proposed in the two subsequent time instances.

The second method, designated Hysteresis Speed Limit Assignment, modifies the policy for speed limit assignment. Assuming the speed limit displayed in the previous time instant is known, the potential intention of speed limit increase can be detected. In that case the VSL would be determined as the equal or nearest lower value (instead of nearest value) from the set $\{60; 80; 100; 120; 130\}$. Otherwise, the original policy is preserved. For example, if the previous speed limit is 60 km/h and the final output of the fuzzy-logic controller for oncoming speed limit is 75.2 km/h, the speed limit 60 km/h will be assigned. The speed limit will be increased in the case that the final output of fuzzy-logic controller reaches at least 80 km/h. The main advantage of this measure lies in the possibility of changing the hysteresis' strength through the thresholds for speed limit increase (the policy described in this paragraph uses the thresholds corresponding directly to the nearest higher speed limits). On the other hand, such an approach is remarkably similar to the decision tree algorithm.

The last method represents a modification of the second method. It reasons its main disadvantage by converting the bivalent logic from Hysteresis Speed Limit Assignment into fuzzy logic. The original architecture from Fig. 1 is extended to the third level, thus including it in the so-called Three-Level Fuzzy Algorithm. A new input variable, VSL_{-1}, representing the speed limit from the previous time instant is introduced. The original output is converted into the second fuzzy auxiliary variable and represents the second input to the third-level fuzzy inference mechanism. The membership functions of the new input variable determine the hysteresis' strength. The rules of the inference mechanism are taken from the bivalent logic previously described. Since the fuzzy-logic controller contains hysteresis measures, the speed limit assignment is performed by the simple speed round (the nearest pre-defined value is assigned).

3. Results from microsimulations

The microsimulations were carried out using the software Aimsun. The algorithms were tested in conditions of the most problematic part of Prague City Ring Road R1 (i.e. from 21.8 km to 14.5 km). In this section, there are a total of six gantries with VMS and detectors, covering the most critical point at 17.0 km. This point is located before Exit 16 where most personal cars get off R1 while heavy trucks continue on the Ring Road. Therefore, congestion and shock waves can often be observed here. It is obvious that traffic volume is higher at peak hours, thus the algorithms were tested in the morning hours from 6 am to 9 am.

Data from the microsimulation model are received every minute, processed, and the resulting speed limits are sent to the VMS located at the gantries, thereby affecting traffic. The level of influence is then given by the parameter of microsimulation model "Driver Compliance". In our case the parameter was set to 0.7 which corresponds to the fact that 30% of drivers do not comply with the speed limit (this fact is observed in the real world measurements). Traffic flow parameters are recorded every minute in order to perform a data analysis and evaluate the impact of the control algorithms. Time series diagrams displaying traffic flow speed and speed limits at the most critical time and point (from 7 am to 9 am, 17.0 km) were drawn in order to perform a visual analysis. Moreover, a survey of fundamental traffic flow parameters completed the visual analysis.

First, the simulation was performed without control. This means that the speed limit of 130 km/h was set during the entire simulation time. The simulation of traffic flow controlled by the INEP algorithm was performed next. Since it represents a mature algorithm, the results of this simulation are used as a reference for the newly developed algorithms. Then, the newly developed set of fuzzy logic algorithms was tested. Since hysteresis emerged as a demanding issue, the fuzzy logic algorithm arising from changeover remains unchanged, while the hysteresis measures vary. Fuzzy algorithm with "Memory" Hysteresis, fuzzy algorithm with

Hysteresis Speed Limit Assignment, and Three-Level Three-Level Fuzzy Algorithm, which introduces the hysteresis at the third level, were successively analyzed.

Fig. 3 provides a comparison of traffic flow without control and controlled by the INEP algorithm. In the case of uncontrolled traffic flow, two sharp speed fluctuations can be observed at about 7:25 and 7:40. It is apparent that the INEP algorithm achieved the suppression of the first fluctuation. In fact, the fluctuation is postponed: it appears later on, but not to the same extent as in traffic flow without control. The INEP algorithm also exhibits a stability with respect to the oscillation of speed limits. The overall time series diagram demonstrates that the traffic flow controlled by the INEP algorithm becomes smoother.

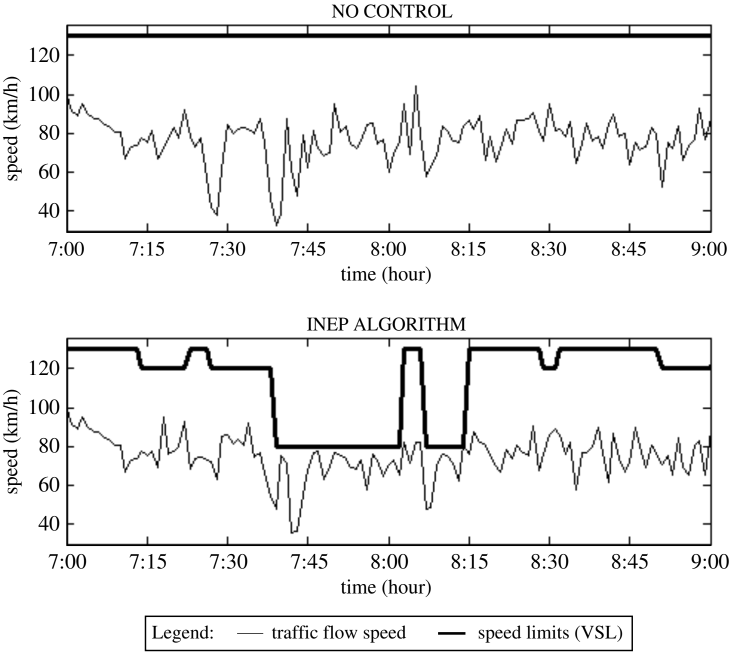


Fig. 3 *Time series of traffic flow speed and VSL at the 17.0 km – traffic flow without control and traffic flow controlled by the INEP algorithm.*

Fig. 4 demonstrates the effect of the fuzzy algorithm with "Memory" Hysteresis (FMEMH), respectively with Hysteresis Speed Assignment (FHSLA). Both algorithms proved their ability to reduce the sharp fluctuation before 7:30. "Memory" Hysteresis prevents only local oscillations, which is not sufficient. However, the traffic flow is smoother than when it is uncontrolled, and the fluctuations after 8:00 are apparent. On the other hand, "Memory" Hysteresis proves to be useful when the very common oscillation between speed limits of 120 km/h and 130 km/h occurs. Hysteresis Speed Assignment leads to smoother traffic flow. Furthermore, in comparison with the INEP algorithm it does not resort to the undesired changes from an 80 km/h speed limit directly to 130 km/h and back to 80 km/h in five minutes (after 8:00). The weakest implication of this method is the mentioned oscillation between speed limits of 120 km/h and 130 km/h.

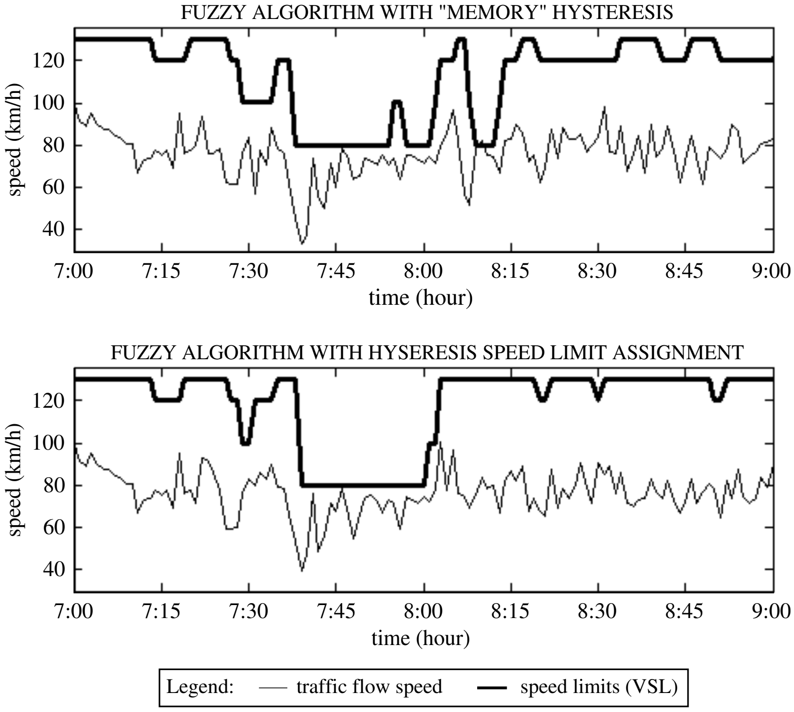
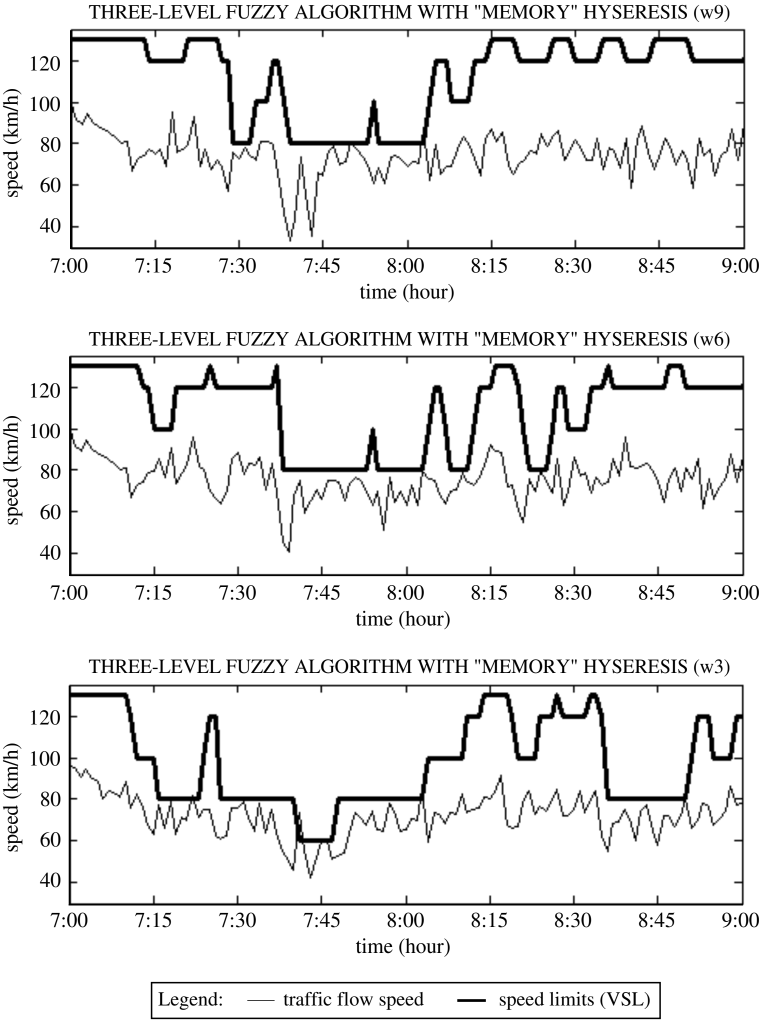


Fig. 4 *Time series of traffic flow speed and VSL at the 17.0 km – traffic controlled by fuzzy algorithm with "Memory" Hysteresis and Hysteresis Speed Limit Assignment.*

The Three-Level Fuzzy Algorithm introduces the hysteresis at the third level. The fuzzy approach does not bring satisfactory results in the first approximation. The Three-Level Algorithm was thus extended by the "Memory" Hysteresis (F3LMH, see the first diagram from Fig. 5). The oscillation of speed limits is still apparent, nevertheless, after 8:00 the traffic flow is smoother than in all previously presented results. Only two significant speed fluctuations can be observed.

The above presented fuzzy algorithms use data aggregated into one-minute intervals and smoothed by the moving average with the window width of nine one-minute samples. It corresponds to the three-minute aggregations and the window width of three samples from the INEP algorithm. It was believed that earlier response of the algorithm could suppress even more fluctuations. Thus, the window width of the moving average applied in the pre-processing phase was reduced from nine to six and three one-minute samples (denoted $w9$, $w6$, and $w3$ respectively). Fig. 5 illustrates the effect of the window width change. Undesired oscillation of speed limits is present, but on the other hand, an earlier response to the traffic can be observed. Moreover, in the case of window width of three, the smoothest traffic flow is achieved and no significant fluctuations in traffic flow speed occur.

Tab. III provides a survey of all presented algorithms with the abbreviations which are used hereinafter for the purpose of the qualitative analysis.



THREE-LEVEL FUZZY ALGORITHM WITH "MEMORY" HYSERESIS (w9)

THREE-LEVEL FUZZY ALGORITHM WITH "MEMORY" HYSERESIS (w6)

THREE-LEVEL FUZZY ALGORITHM WITH "MEMORY" HYSERESIS (w3)

Fig. 5 *Time series of traffic flow speed and VSL at the 17.0 km – traffic controlled by Tree-Level Fuzzy Algorithm with "Memory" Hysteresis.*

Algorithm	Abbreviation
INEP algorithm	INEP
Fuzzy algorithm with "Memory" Hysteresis	FMEMH
Fuzzy algorithm with Hysteresis Speed Limit Assignment	FHSLA
Three-Level Fuzzy Algorithm with "Memory" Hysteresis, w9	F3LMw9
Three-Level Fuzzy Algorithm with "Memory" Hysteresis, w6	F3LMw6
Three-Level Fuzzy Algorithm with "Memory" Hysteresis, w3	F3LMw3

Tab. III *Survey of tested algorithms.*

Three fundamental parameters of traffic flow were analyzed for each presented algorithm. Average values and standard deviations (StDev) of speed, intensity and density were calculated and related to the uncontrolled traffic flow (see Tab. IV). Whereas average speed slightly decreased, the standard deviation of speed decreased significantly. This phenomenon in data indicates speed harmonization, which leads to safer traffic flow. Although F3LMw3 proves more significant decrease in average speed, average intensity (number of passing vehicles) slightly increased. Thus, the decrease of average speed is still acceptable. Furthermore, the decrease in the standard deviation of density and intensity, while almost remaining their average values, can be interpreted as the suppression or partial suppression of shock waves.

	Average speed [%]	Speed StDev [%]	Average intensity [%]	Intensity StDev [%]	Average density [%]	Density StDev [%]
INEP	−1.85	−10.53	+0.10	+0.34	+0.44	−7.42
FMEMH	−0.90	−6.72	+0.03	−2.83	−0.47	−6.37
FHSLA	−0.28	−12.25	+0.19	−3.09	−2.15	−15.06
F3LMw9	−2.52	−13.51	+0.12	−3.10	+0.29	−9.15
F3LMw6	−0.92	−16.19	−0.05	−4.18	−1.60	−17.92
F3LMw3	−5.59	−17.38	+0.20	−10.18	+3.17	−18.45

Tab. IV *Comparison of the controlled traffic flow with respect to the non-controlled traffic flow.*

According to the results in Tab. IV, the most significant speed harmonization was achieved by the algorithm F3LMw3 (Three-Level Fuzzy Algorithm with "Memory" Hysteresis and w3). Thus, this algorithm was selected for another visual analysis where it is compared by means of time-space diagrams with the INEP algorithm and the uncontrolled traffic flow.

Fig. 6 illustrates the speed harmonization in the most critical segment before the 17.0 km point. The time axis corresponds to the time-series diagrams, and the space axis represents the segment of R1 where three gantries are located (driving direction is from 20.1 km to 17.0 km). The special marks in the figure indicate the speed limits displayed at the respective VMS, and the differences in the shades of gray represent the speed fluctuations. The darkest areas representing the sharp speed fluctuations partially disappears and disappears applying INEP and F3LMw3 respectively. It is also apparent that the gray tones become more continuous (smooth), which indicates the speed harmonization.

4. Conclusions

This paper provides a detailed description of the process in which a decision tree control algorithm was transformed into a fuzzy control system. The changeover from bivalent logic to fuzzy logic was demonstrated on the existing INEP algorithm, achieving a significant improvement of the existing algorithm.

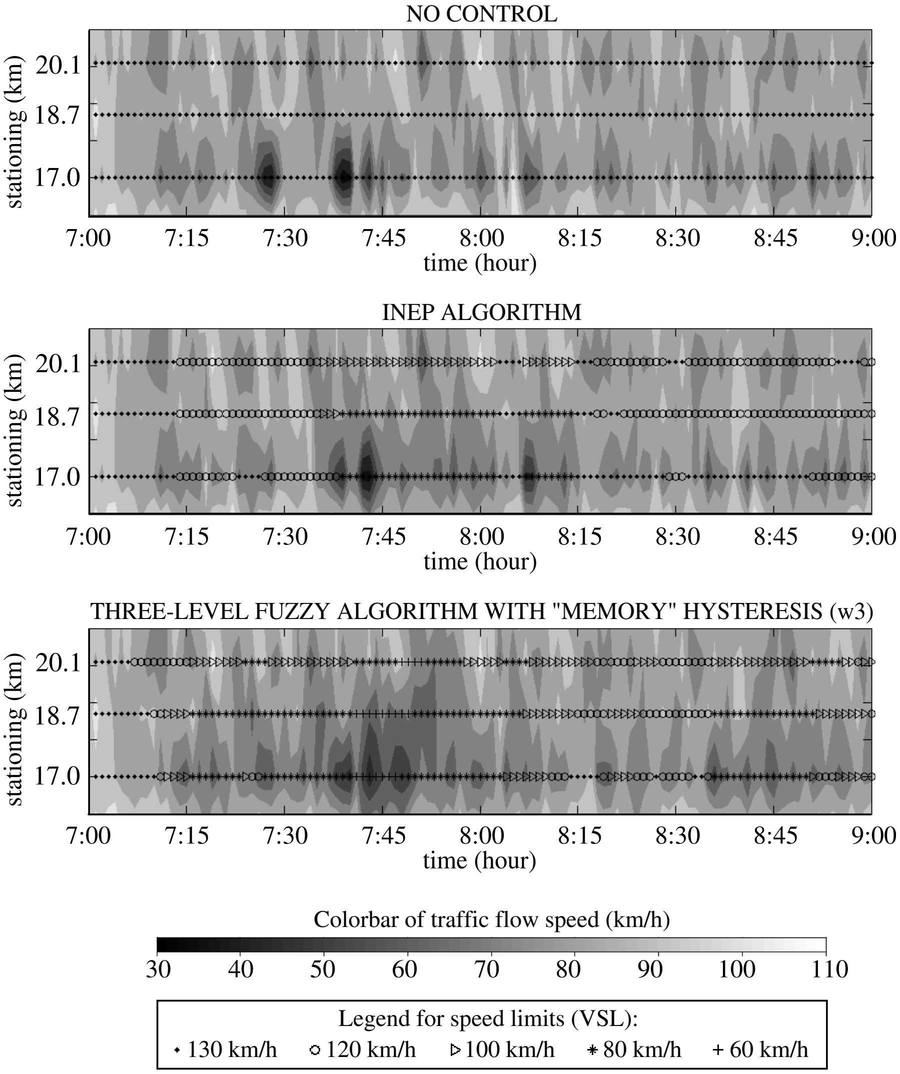


Fig. 6 *Time-space contour diagrams of traffic flow speed – comparison of traffic flow without control, controlled by INEP algorithm, and controlled by Three-Level Fuzzy Algorithm.*

While performing the changeover, the hysteresis was identified as the most demanding issue. Thus, one fuzzy logic algorithm was developed as a result of the direct changeover and it was tested applying successively three proposed hysteresis measures: “Memory” Hysteresis, Hysteresis Speed Limit Assignment, and Three-Level Fuzzy Logic Algorithm, which introduces the hysteresis at the third level. Furthermore, different levels of smoothing in pre-processing were tested. It was confirmed that reduced level of smoothing results in an earlier response of the algorithm.

Based on the results from microsimulations, it can be concluded, that the Three-Level Fuzzy Algorithm with "Memory" Hysteresis and $w3$ is the most suitable control system for speed harmonization. It leads to a stable behavior and overall smoothing of the measured speeds. This is confirmed by the time-space diagram of the measured speeds and by the analysis of traffic flow parameters.

In the next steps, the proposed algorithm will be recommended for testing and evaluation in real conditions on the Prague City Ring Road. At the same time, the fuzzy algorithm offers several objects for improvement, such as tuning of fuzzy sets, introducing new input variables, or reaching a compromise between hysteresis strength and smoothing level in pre-processing.

Acknowledgement

This research is financially supported by the internal grant of the Czech Technical University in Prague SGS15/169/OHK2/2T/16.

References

[1] ALLABY P., HELLINGA B., BULLOCK M. *Variable speed limits: Safety and operational impacts of a candidate control strategy for freeway applications.* IEEE Transactions on ITS. 2007, 8(4), pp. 671–680, doi: `10.1109/TITS.2007.908562`.

[2] BROWN M., BOSSLEY K.M., MILLS D.J., HARRIS C.J. High dimensional neurofuzzy systems: overcoming the curse of dimensionality. In: *Proceedings of Joint Conference of the 4th International Conference on Fuzzy Systems and the 2nd International Fuzzy Engineering Symposium*, Yokohama, Japan. IEEE, 1995, 4, pp. 2139–2146, doi: `10.1109/FUZZY.1995.409976`.

[3] BUNDESANSTALT FÜR STRASSENWESSEN. *MARZ: Merkblatt für die Ausstattung von Verkehrsrechnerzentralen und Unterzentralen.* Bergisch Gladbach: BASt, 1999. In German.

[4] CHIEN C.C., IOANNOU P., CHU C.K. Fuzzy traffic density homogenizer for automated highway system. In: *Proceedings of the 3rd IEEE Conference on Fuzzy Systems*, Beijing, China. IEEE World Congress on Computational Intelligence, 1994, 2, pp. 968–973, doi: `10.1109/FUZZY.1994.343866`.

[5] ELTODO EG, A.S. *Projct INEP* [online]. 2009 [viewed 2015-06-19]. Available from: `http://eltodo.cz/`

[6] GU S., MA J., WANG J., SUI X., LIU Y. *Methodology for variable speed limit activation in active traffic management.* Procedia - Social and Behavioral Sciences. 2013, 96, pp. 2129–2137, doi: `10.1016/j.sbspro.2013.08.240`.

[7] HIGHWAYS AGENCY. *M25 Controlled Motorways* [online]. Issue 1, November 2004 [viewed 2015-06-19]. Summary report HA159/04. Available from: `http://www.standardsforhighways.co.uk/pilots_trials/files/ha2004.pdf`

[8] JIANG R., CHUNG E., LEE J.B. Variable speed limits: Conceptual design for Queensland practice. In: *Proceedings of the 34th Australasian Transportation Research Forum 2011 (ATRF 2011)*, Adelaide, Australia, 2011 [viewed 2015-06-19]. Available from: `http://www.atrf11.unisa.edu.au/Assets/Papers/ATRF11_0125_final.pdf`

[9] JO Y., CHOI H., JEON S., JUNG I. Variable speed limit to improve safety near traffic congestion on urban freeways. In: *Proceedings of 2012 IEEE International Conference Information Science and Technology (ICIST)*, Wuhan, China. IEEE, 2012, pp. 43–50, doi: `10.1109/ICIST.2012.6221605`.

[10] KÜHNE R.D., LANGBEIN K. *Optimierung der Parameter einer Linienbeeinflussungsanlage.* Tagungsbericht Heureka 93, Karlsruhe, 1993, pp. 116–139. In German.

[11] KUKLOVÁ J., PŘIBYL O. *Development of highway management in the Czech Republic towards multi-agent approach.* World transport and technological machinery. 2014, 4(47), pp. 109–115.

[12] PAPAGEORGIOU M., KOSMATOPOULOS E., PAPAMICHAIL I. *Effect of variable speed limits on motorway traffic flow.* Transportation Research Record. 2008, 2047, pp. 37–48, doi: `10.3141/2047-05`.

[13] PLACER J. *Fuzzy variable speed limit modification and testing - Phase II.* Final report 466(2), Arizona: Department of Computer Science and Engineering, 2001.

[14] PLACER J., SAGAHYROON A. *Fuzzy variable speed limit device project.* Report no. FHWA-AZ98-466, Arizona: Department of Computer Science and Engineering, 1998.

[15] ROSHANDEH A.M., JOSHANI M., PUAN O.C. Fuzzy logic system for variable message signs in Kuala Lumpur. In: *Proceedings of the 3rd International Conference on European Computing Conference (ECC'09)*, Tbilisi, Georgia, USA. Wisconsin: WSEAS, 2009, pp. 209–214.

[16] SALA A.A., GUERRA T.M.B., BABUŠKA R.C. *Perspectives of fuzzy systems and control.* Fuzzy Sets and Systems. 2005, 156(3), pp. 432–444, doi: `10.1016/j.fss.2005.05.041`.

[17] SOLTÉSZ T., KÓZEL M., CSISZÁR C., CENTGRÁF T., BENYÓ B. *Information system for road infrastructure booking.* Periodica Polytechnica Transportation Engineering. 2011, 39(2), pp. 55–62, doi: `10.3311/pp.tr.2011-2.02`.

[18] SMULDERS S. *Control of freeway traffic flow by variable speed signs.* Transportation Research Part B: Methodological. 1990, 24(2), pp. 111–132, doi: `10.1016/0191-2615(90)90023-R`.

[19] TAKAGI T., SUGENO M. *Fuzzy identification of systems and its applications to modeling and control.* IEEE Transactions on Systems, Man and Cybernetics. 1985, SMC-15(1), pp. 116–132, doi: `10.1109/TSMC.1985.6313399`.

[20] VUCANOVIC S., KATES R., DENAES S., KELLER H. A novel algorithm for optimized, safety-oriented dynamic speed regulation on highways: INCA. In: *Proceedings of 2005 IEEE Intelligent Transportation Systems Conference (ITSC 2005)*, Vienna, Austria. IEEE, 2005, pp. 260–265, doi: `10.1109/ITSC.2005.1520078`.

[21] WANG Y., BIN W., HUI Y. The national freeway control system – Further development with fuzzy logic theory. In: *Proceedings of the IEEE International Conference on Industrial Technology (ICIT'94)*, Guangzhou, China. IEEE, 1994, pp. 729–733, doi: `10.1109/ICIT.1994.467044`.

[22] ZADEH L.A. Fuzzy sets. *Information and Control.* 1965, 8(3), pp. 338–353, doi: `10.1016/S0019-9958(65)90241-X`.