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Teoretické základy a řešení ke zlepšení bezpečnosti dopravy a dynamiky dopravního proudu

Theoretical fundaments and solutions to improve road safety and the dynamics of traffic flow

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Summary

The author presents his experiences from design and evaluation of the first highway management system in the Czech Republic. After a short theoretical introduction dealing with the topics of traffic flow parameters and the way of influencing them by general highway management strategies, a modular highway management system is introduced. Solutions to one of the key modules – speed harmonization – are described; decision tree based approach as well as fuzzy-logic based approaches. The algorithm and the modular structure developed by the author as part of a research project was implemented on the Prague city ring, where it has been in operation since 2010.
Since we are talking about the first implementation in the Czech Republic, an evaluation of its impact and driver's reactions had not been well known. At the same time, the drivers' compliance influences the design of variable speed limit systems as well as any evaluation in microscopic simulation models, where it is an important input value. For such reasons, the author focused on evaluation of the highway management system in a simulated as well as in the real environment. The focus is on the influence of a highway management system on traffic safety and the dynamics of traffic flow. Among others, changes in so-called fundamental diagram have been studied in order to determine the impact of such system on road capacity.
Finally, the author presents next steps that are relevant for given field and will be conducted within his team at the Czech Technical University in Prague.

Souhrn

V této práci autor prezentuje své zkušenosti s návrhem a vyhodnocením prvního systému liniového řízení dálnic implementovaného v České republice. Po krátkém teoretickém úvodu zabývajícím se parametry dopravního proudu a jednotlivými strategiemi systému managementu dálnic je představen nový modulární systém pro management dálnic. Hlavní důraz je kladen na návrh základního modulu takového systému – systému pro harmonizaci rychlosti. Autor představuje dva přístupy k řešení založené na rozhodovacích stromech a fuzzy logice. Algoritmus i modulární struktura systému vyvinuté autorem jako součást výzkumných projektů byly následně implementovány na Silničním okruhu kolem Prahy, kde jsou od roku 2010 stále v provozu.

Vzhledem k tomu, že jde o první realizaci v České republice, hodnocení jejího vlivu na řidiče a dopravní proud nebylo v reálných podmínkách dosud zpracováno. Zároveň je prokázáno, že úroveň dodržování předepsaných rychlostních limitů má přímo vliv na účinnost celého systému. Z těchto důvodů se autor zaměřil na vyhodnocení systému liniového řízení s využitím dopravních dat z reálného provozu. Tato data vstupovala i do mikroskopických simulačních modelů.

V závěru autor popisuje další kroky, které budou v daném oboru rozvíjeny na jeho pracovišti.

Keywords:

Highway management; traffic flow; fundamental diagram; soft computing

Klíčová slova:

Management dálnic; dopravní tok; fundamentální diagram; soft computing

Contents

1 Introduction and motivation

This work focuses on measures for improvement of highway safety and capacity using telematics systems (also known as Intelligent Transportation Systems - ITS) without the need to build new road infrastructure. Before we discuss the highway management algorithms and strategies, let us look at the major traffic flow characteristics. They are essential for understanding the influence of any control strategy on traffic.

1.1 Traffic flow characteristics and fundamental diagram

In order to understand how the different control measures influence traffic, we have to describe basic traffic flow parameters and the relationship among them. Selected basic traffic flow characteristics are discussed in the following section (Ni, 2016):

Traffic count (N) [veh] is the number of vehicles counted by a sensor. Traffic count can be converted to the hourly equivalent rate of flow (q) as $q = N/T$, where T denotes observation period (typically an hour).

Flow (q) [veh/hour] is the rate at which vehicles pass a given point on the roadway per unit of time.

Density (k) [veh/km] refers to the number of vehicles present on a unit length of road and can be determined as $k = N/L$, where L denotes the length of stretch of the road under observation.

Speed (v) [km/hour] is defined as the distance a vehicle travels per unit of time and can be expressed as $v = \frac{1}{N}\sum_{i=1}^{N} \dot{x}_i$, where $\dot{x}_i$ denotes the speed of individual vehicles expressed as $\dot{x}_i = dx/dt$, where x is position of the vehicle.

Occupancy (o) [%] is defined as the percentage of time when there is a vehicle present above the sensor, τ_i, and is computed as $o = \frac{1}{T}\sum_{i=1}^{N}\tau_i$.

1.2 Basic equation

The basic equation expressing the relationship among flow, speed and density holds as an identity

$$q = k \times v. \tag{1.1}$$

1.3 Relationship among density and occupancy

Measurement of density is rather problematic in the real world as it is a spatial characteristic requiring an image of the entire road section under observation. In most practical applications, the occupancy, that is obtained by a single sensor) is used instead. This is based on the assumption, that we know the active length of the sensor d, and that we know an uniform length of the passing vehicles $l_i = l$.

$$\begin{aligned} o = \frac{1}{T}\sum_{i=1}^{N}\tau_i = \frac{1}{T}\sum_{i=1}^{N}\frac{d+l_i}{\dot{x}_i} \approx \frac{d+l}{T}\sum_{i=1}^{N}\frac{1}{\dot{x}_i}\,(assume \quad l_i \to l) \\ = (d+l)\,\frac{1}{T}\sum_{i=1}^{N}\frac{1}{\dot{x}_i} = (d+l)\,\frac{N}{T}\frac{1}{N}\sum_{i=1}^{N}\frac{1}{\dot{x}_i} = (d+l)\,q\frac{1}{v} \\ = (d+l)\,k. \end{aligned} \tag{1.2}$$

According to the previous deduction, based on the above mentioned assumptions, it is obvious that occupancy is proportional to the density with a coefficient equal to the sum of loop length d and the uniform vehicle length l. This is important as the graphs from the real-world measurements within this work based on this assumption are using occupancy.

1.4 Fundamental diagram

A figure depicting the relationship among the traffic flow parameters is so-called fundamental diagram (Kühne, 2011). For the first time, it was empirically observed and described by Greenshields (Greenshields, 1935). This model was based on measurement of speed and flow, used to compute the density (based on equation 1.1). The measurement was rather complicated as was conducted by taking pictures by a 16mm camera with an additional electromotor and measuring the time between snapshots. For more details, please refer to (Kühne, 2011). The measurements and the proposed linear relationship among speed and density is depicted in Fig. 1.1.

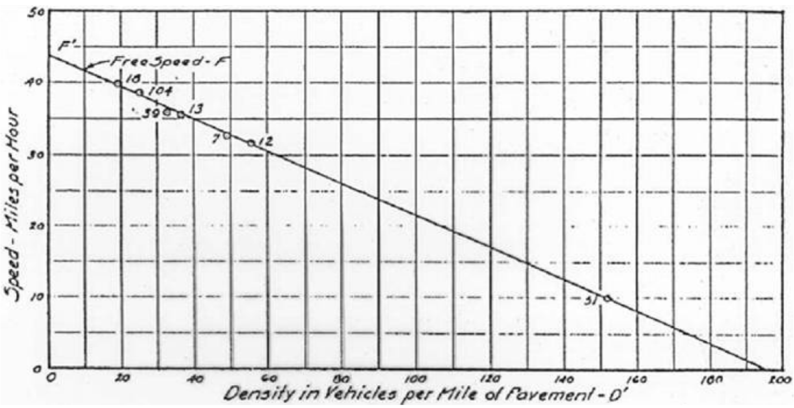


Figure 1.1: Original measurements and the speed-density relationship proposed by Greenshields, 1935

The linear function is completely determined by just two points of intercept: $(k = 0, v = v_f)$ and $(k = k_j, v = 0)$, where v_f denotes the free flow speed (i.e. the desired speed without being influenced by adjacent vehicles) and k_j is the jam density (i.e. the density by stop-and-go traffic situation). The actual speed of the vehicle can be expressed by the following equation:

$$v = v_f \left(1 - \frac{k}{k_j}\right), \tag{1.3}$$

where v_f denotes the free flow speed and k_j is the jam density.

When we apply the identity from equation 1.1, the relationship among flow and density can be expressed as follows:

$$q = v_f \left(k - \frac{k^2}{k_j} \right). \tag{1.4}$$

The resulting relationship between flow and density is a quadratic function as depicted in Fig. 1.2, c.

Similarly, we can eliminate density k from the equation 1.3 by using equation 1.1 and express the relationship between speed and flow as follows (depicted in Fig. 1.2, b.):

$$q = k_j \left(v - \frac{v^2}{v_f} \right). \tag{1.5}$$

When looking at Fig. 1.2, we can point out some important points and areas in the relationships:

- v_f is so called free flow speed, in other words the desired speed,
- v_m is called optimal speed when the flow reaches the capacity of the road,
- q_m is the maximal flow also denoted as capacity of the given road,
- k_m is the critical density when the maximal flow is reached,
- k_j is a jam density for which the speed equals to zero.

If the density is lower than the critical density k_m the traffic flow is called to be stable (Papageorgiou, Kosmatopoulos, and Papamichail, 2008). This is an important feature that will be further evaluated on the real measurements and data. The slope of a line that connects the particular point on the traffic condition curve with the origin in the flow-density (resp. flow-occupancy) diagram gives the mean speed of that traffic flow.

Due to its simplicity and clarity, the Greenshields model is clearly the most often cited one and one used in praxis as well as in theoretical works. Many researchers however aimed on improvement of the fitting of the model to the real data. There are other researchers who aimed on fitting in a single mathematical function (for this reason they are known as Single-regime models), such as Greenberg‘s

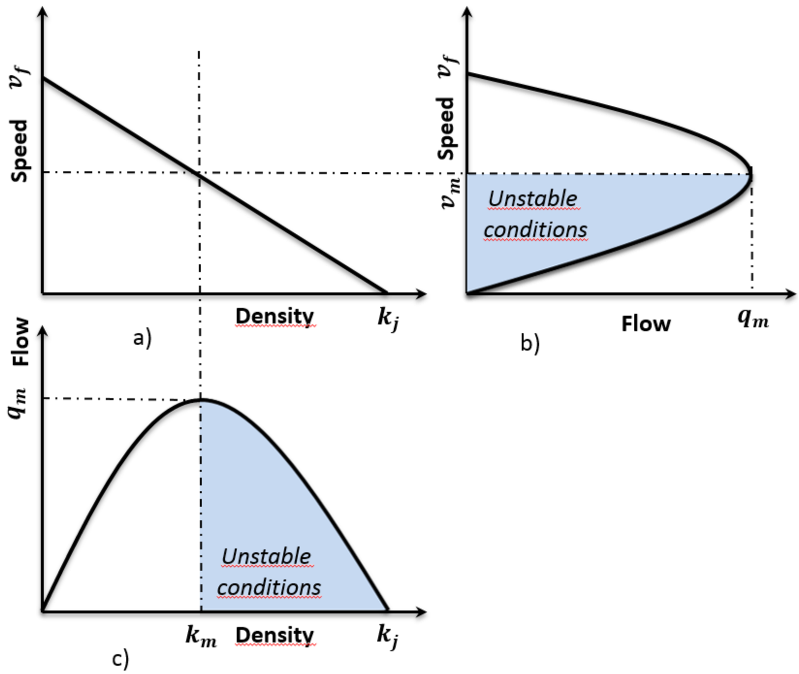


Figure 1.2: The fundamental diagram (own source)

logarithmical model, or Underwood's exponential model. Since each of the single-regime models is working well for different density regions, several researchers proposed so-called Multi-regime models. Here, different functions are used to fit different density areas, such as Eddie model or Three-regime model. These models are however not further investigated in this work as it is not its core objective (for more details, please refer to (Ni, 2016). We focus on the Greenshields fundamental diagram as a tool to evaluate the speed harmonization strategies.

1.5 Overview of highway management system strategies

In the previous parts we discussed some of the characteristics of the traffic flow. This was done with one major objective in mind – to propose a highway management system which would improve the characteristics of the traffic flow. Highway management systems (HMS) have become very popular in the recent years. There are several reasons for this trend. Even though the number of vehicles and the kilometres travelled are increasing continuously, it is not possible to keep increasing the road capacity by simple building new roads. Additional measures, typically from the ITS field must be introduced. And that is the case of highway management systems. HMSs are typically addressing one or more of the following objectives:

1. decreasing the number and impact of regular congestions (e.g. increase of capacity),
2. decreasing the number and impact of irregular congestions (e.g. traffic accidents),
3. increasing traffic safety.

It shall be pointed out that we are dealing with a multicriteria optimisation, where particular criteria are often contradictory. For example, the safest highway system will have average speed (and thus throughput) equal to zero. The objective function is thus aiming on the different contradictory aims, i.e. cost, environmental impact and safety). HMSs are using whole set of strategies to achieve these objectives. An overview of the strategies (O. Přibyl, 2010) is provided in Fig. 1.3.

1.6 Motivation for research

Highway management systems have been implemented in several countries. In the year 2008 when the author was starting his work on this topic, there was however no such system implemented in the Czech Republic. The theoretical impact as well as practical experiences from the real-world projects were encouraging. Some results from a study summarizing results from many international projects

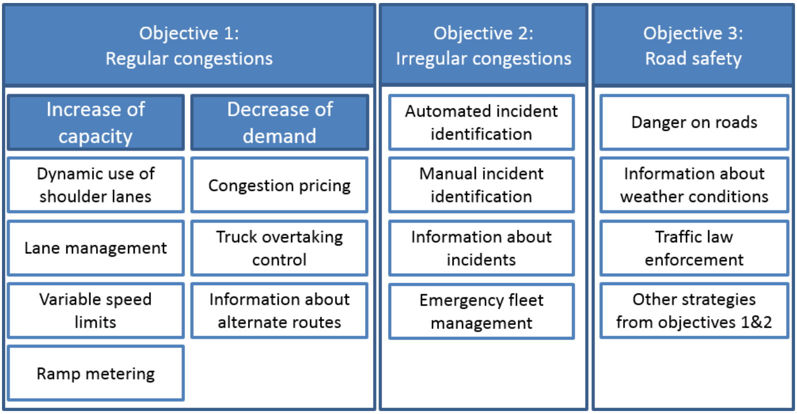


Figure 1.3: Major highway management objectives and strategies (adopted from: O. Přibyl, 2010)

(FHWA, 2003) indicate for example decreased travel time by 20% to 48%, decreased time to clear a traffic accident on average by 23 minutes (corresponds to 50%), or increased highway capacity by 17% to 25%.

Such promising results and the need for such system with the scheduled building of the new Prague city ring were the original impulse why the author focused on the topic of highway management, particularly on the speed harmonization. The research builds on his previous experiences from the field of soft computing, transportation planning, data processing, intelligent transportation systems (ITS) or mathematical modelling. In this complex problem, the author's interdisciplinary background is of advantage. The research covered several important topics, such as:

- data collection and pre-processing (including sensor's design) (Kučera and O. Přibyl, 2006), data smoothing, cleaning, reduction, and others),
- proposal of a mandatory design methodology for building ITS systems (P. Přibyl, O. Přibyl, and Bureš, 2010),
- design of a modular structure of the HMS (O. Přibyl, 2010),

- design of the algorithm, which is currently implemented on the only highway management system in the Czech Republic,
- design and evaluation of algorithms based on fuzzy logic,
- design of evaluation criteria for speed harmonization algorithms (O. Přibyl and Krajčír, 2013),
- implementation of the Prague city ring (including the control algorithms) in a microsimulation model, its calibration and evaluation of results,
- and others.

The presented work is the result of different research projects such as INEP (CG944-033-120) supported by the Ministry of Transport in the Czech Republic, project SIRID (TA02030522) supported by the Technological Agency of the Czech Republic, or two student grants SGS15/169/OHK2/2T/16 and SGS16/186/OHK2/2T/16. The work on the research projects allowed us to have a better understanding of how different stakeholders (for example the highway administration, the transportation police, or the operators dealing with the implemented system on the daily bases) perceive the implemented highway management system. This was an important input to the second generation of the algorithms.

The author also guided several of his students who participated on the research focusing on particular aspects of the speed harmonization, such as Jiří Beneš, Jana Kuklová, Milan Koukol and others. The objective was to build at the university a research group able to deal with the tasks related to highway management systems. Several publications, including impacted publications, were the result of this work.

In the next chapters of the presented work, some of the results, mainly the two generations of the speed harmonization system and the results are described and discussed.

2 Algorithms and methods

2.1 Algorithms for highway management

First proposal of a highway management system for an installation in the Czech Republic was prepared as part of the research project INEP (CG944-033-120) conducted in the years 2009-2010. The objectives of the project covered a study of existing implementations of HMS and their impact on traffic, proposal of an algorithm for speed harmonisation and automated incident detection, design of the physical architecture (gantries, traffic signs, etc.) and some basic evaluation of the proposed system.

The author of this work was part of the project team from the company ELTODO and the Czech Technical University in Prague, Faculty of Transportation Sciences where he was responsible especially for design of the algorithms, modular design of the HMS and data processing part.

Based on this project, the first highway management system in the Czech Republic was implemented and put into operation by October 2010. The system was installed on 35 kilometres of the Prague city ring connecting the highways D1 and D5. It is an important part of road infrastructure, since the transit drivers can now bypass Prague completely. There are overall 45 gantries with 255 variable message signs (VMS), 105 inductive loops (traffic sensors), 33 CCTV cameras, 12 meteostations and other technology. A new highway management centre was built in Rudná u Prahy, where SCADA control system and over 20 large screens and 26 monitors allow for continuous monitoring of the traffic conditions and verification of the control measures on the Prague city ring (Fig. 2.3). The cost of the technological part of the system was about 280 million Czech crowns.

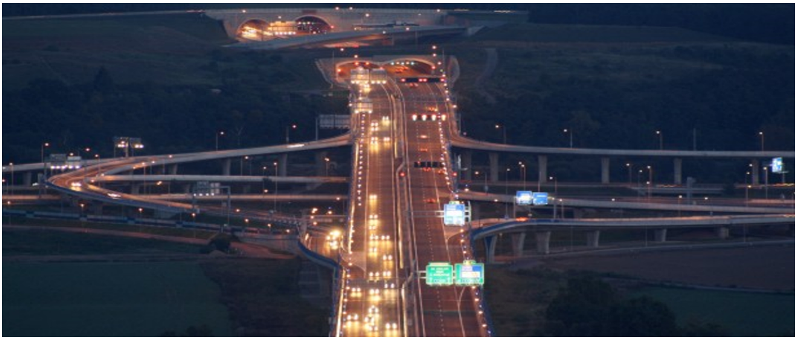


Figure 2.1: Picture of the implementation of the HMS on the Prague city ring (source: Mr. Podroužek)

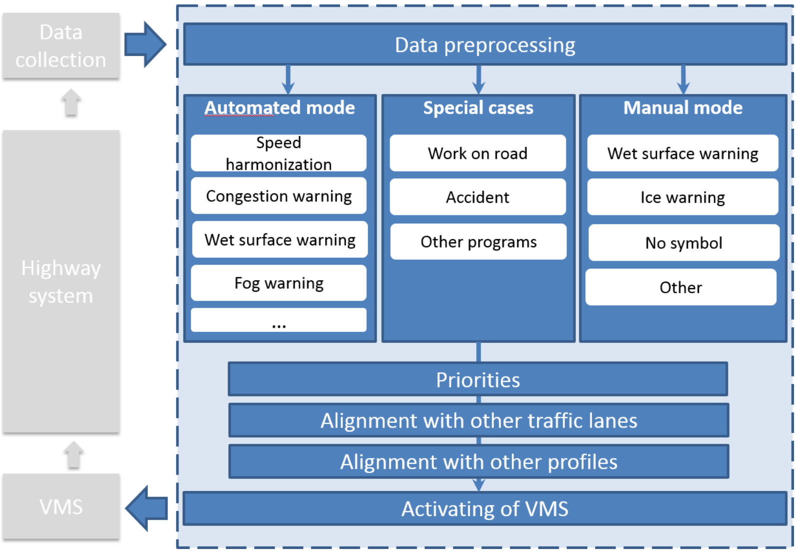


Figure 2.2: Modular scheme of the highway management system proposed by the author and implemented on the Prague city ring

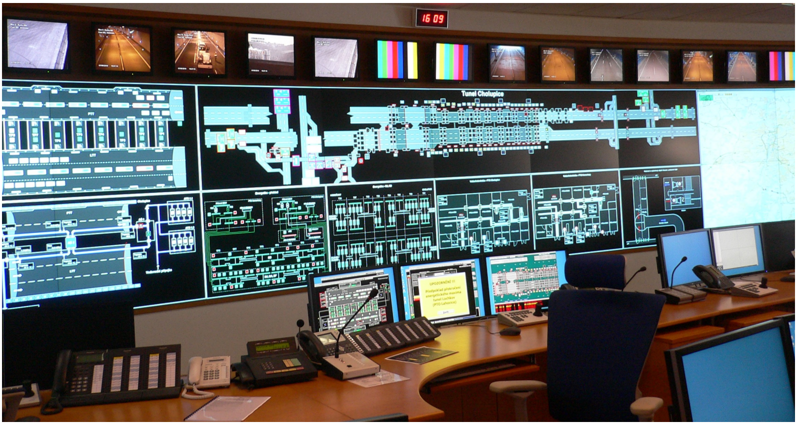


Figure 2.3: Photo of the implemented highway management center in Rudná u Prahy (own source)

2.2 Algorithms for speed harmonisation

2.2.1 Decision tree based algorithms

During the project INEP many different algorithms for speed harmonisation were evaluated (for example based on Allaby, Hellinga, and Bullock, 2006; Vukanovic et al., 2005). The algorithm design was based on several requirements collected mostly from the highway administration (ŘSD). The most important criteria are provided below:

1. The algorithm shall be understandable by experts.
2. The algorithm shall be configurable (easy changes through dedicated parameters).
3. The algorithm shall be compliant with existing standards in the Czech Republic.

Based on these criteria, the logic of the proposed algorithm is using decision trees, presented in a form of a table in Fig. 2.3. This is also an approach recommended by the German technical norms Technische Lieferbedingungen für Streckenstationen (TLS), 2002, which makes it more acceptable for the customer of the system - ŘSD. The algorithm is using three characteristics of traffic flow. They are computed/predicted based on the measured data (please note, that the capital letters denote aggregation over all lanes in a given direction of traffic)(O. Přibyl, 2007a):

- $\tilde{Q}_B$ is flow for given direction of traffic expressed as the equivalent of personal vehicles (denoted by the index B). This means that flow of trucks is recomputed through usage of predefined coeeficients.

- $\tilde{D}$ is traffic density computed form values of speed and flow in given direction of traffic.

- $\tilde{V}_{OS}$ is mean speed of personal vehicles during an observation period (3 minutes within the INEP project).

- The output of the algorithm is then the speed limit imposed by the traffic sign B20a on a variable message sign (VMS).

The logic of the algorithm is described in Fig. 2.4. An important aspect of this logic is in using different criteria for turning on and off a speed limit. This is an in-built hysteresis important to minimize oscillation in situations where the input variables are near the decision boundaries.

The actual values of parameters $Q_{B,X}^{ON/OFF}$ were initially estimated based on results of a microsimulation experiments and modified by experts during the pilot evaluation of the project.

2.2.2 Fuzzy logic based algorithms

The proposed decision tree based algorithm for speed harmonization was successfully implemented on the Prague city ring. The authors were however aware of its straightforwardness (actually required by the customers) and some limitations. One of the major reasons is in the crisp boundaries in the decision rules. Random presence of a small group of vehicles can result in turning on certain speed limit. Additionally, during the operation, several other possible improvements were identified, such as shorter period for aggregation of traffic values (3 minutes in the original algorithm) and others. Based on this in the years 2012-2015 a new research project supported by the Technological Agency of the Czech Republic was conducted: SIRID – Development of a new generation of a speed harmonisation algorithms and a

Display on VMS	$\widetilde{Q}_B(i)$ OR ($\widetilde{V}_{os}(i)$ AND		$\widetilde{D}(i)$)
120	$\geq Q^{ON}{}_{B,120}$		
100	$\geq Q^{ON}{}_{B,100}$	$\leq V_{100}^{ON}$	$\geq D_{100}^{ON}$
80	$\geq Q^{ON}{}_{B,80}$	$\leq V_{80}^{ON}$	$\geq D_{80}^{ON}$
60	$\geq Q^{ON}{}_{B,60}$	$\leq V_{60}^{ON}$	$\geq D_{60}^{ON}$

a)

Display on VMS	$\widetilde{Q}_B(i)$ OR ($\widetilde{V}_{os}(i)$ AND		$\widetilde{D}(i)$)
120	$< Q^{OFF}{}_{B,120}$		
100	$< Q^{OFF}{}_{B,100}$	$> V_{100}^{OFF}$	$< D_{100}^{OFF}$
80	$< Q^{OFF}{}_{B,80}$	$> V_{80}^{OFF}$	$< D_{80}^{OFF}$
60	$< Q^{OFF}{}_{B,60}$	$> V_{60}^{OFF}$	$< D_{60}^{OFF}$

b)

Figure 2.4: Decision tree based algorithm for a) turning on and b) turning off particular speed limits as proposed in the project INEP and implemented on the Prague city ring

test environment (TA02030522). The author was responsible mainly for development of new algorithms for speed harmonization based on fuzzy logic and their evaluation. Such new algorithms evolved from the analysis of the existing system and its results, but also on detailed data analysis as well as literature review (O. Přibyl, Koukol, and Kuklová, 2015).

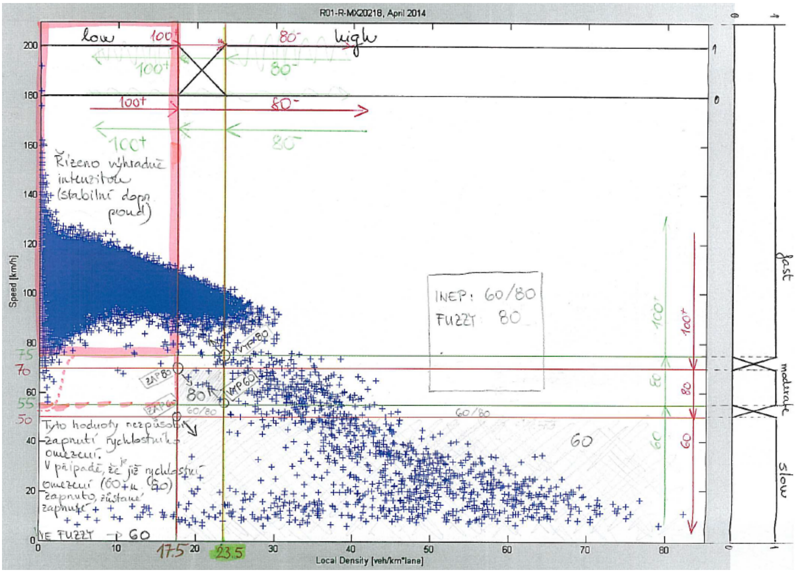


Figure 2.5: Example of the measured data and the experimental design of fuzzy rules

There were many different algorithms developed and tested within this project. Expert knowledge resulting from the experiences with the existing speed harmonization system and data analysis was used to set their structure and parameters (example measured fundamental diagram used for setting the parameters of the model is provided in Fig. 2.5). The proposal of the rule base was based on several key assumptions:

- If the speed drops below certain threshold (e.g. 55 km/h), the variable speed limit system (VSL) shall display the speed limit 60 km/h, so that the speed of the vehicles arriving to the platoon of vehicles and the speed of the entire platoon do not differ significantly.
- The existing literature (Bertini, Boice, and Bogenberger, 2006; Papageorgiou, 1997; Lindgren, 2005) as well as own experiments demonstrated that the maximal capacity of a highway segment is reached for speeds between 80 and 90 km/h. For

this reason, if the traffic flow is near the critical density, the VSL shall display speed limit 80 km/h.

- The speed limits 100 km/h and 120 km/h aim on the speed harmonization prior to actual traffic instability. This also increases drivers' attention.

- It has been experimentally proven (Matowicki and O. Přibyl, 2016) that drivers comply better with imposed speed limits if additional information about the reason for the speed limitation is provided. For this reason, additional signs warning about queues (sign A23), work on road (sign A15) or traffic accidents (sign A27) shall be provided together with the speed limit.

So-called **Takagi-Sugeno fuzzy inference system** (FIS) was used in our models. The fuzzy rules have the following general structure:

$$\text{IF} \quad x_i \quad \text{is} \quad A_i \quad \text{THEN} \quad y = f_i\left(x\right), \quad i = 1, 2, ..., K. \tag{2.1}$$

Compared to the most typical type of inference system, Mamdani FIS, where the output is a fuzzy variable, the Takagi-Sugeno model has a function f of the input variables x as an output. In case the function is linear, the fuzzy rules can be written as:

$$\text{IF} \quad x_i \quad \text{is} \quad A_i \quad \text{THEN} \quad y_i = A_i^T x + b_i, \quad i = 1, 2, ..., K. \tag{2.2}$$

In our case we decided to use so-called singleton as the output function. It is a special case in which the coefficients $a_i = 0$ and the output equals to the constant value b (Zadeh, 1965; Babuška, 1998). The singleton values in our case equal directly to the imposed speed limits, which takes only selected crisp values (60 km/h, 80 km/h, etc.). This inference mechanism is straightforward and the resulting defuzzification is simple (weighted average as described below).

The following parameters are common for all the proposed fuzzy control algorithms (Jang, Sun, and Mizutani, 1997):

- Trapezoidal membership functions were used, also because a direct implementation of the FIS in microscopic simulation was proposed as part of the solution (Koukol and O. Přibyl, 2013).

- Product is used as the t-norm operator in the FIS.

- Weighted average method was used for defuzzification:

$$y = \frac{\sum_{i=1}^{n} m_i w_i}{\sum_{i=1}^{n} m_i}, \tag{2.3}$$

where y is the crisp output value (imposed speed limit), m_i is the degree of membership from the interval $< 0, 1 >$ of fired fuzzy rules to given output, and w_i is the weight of given fuzzy rule.

There are however some basic differences in the design of particular fuzzy control algorithms, as briefly summarized in the following paragraphs.

1. Different input variables

In the models, different input variables were tested. First, a simple algorithms based on occupancy (O) and flow (Q) only, were proposed (the capital letters indicate aggregation over the entire road profile). Next, algorithms using the same variables as the above mentioned INEP model were designed. Also the influence of using directly measured occupancy instead of computed density was evaluated.

2. Different model structure (hierarchy)

The first model structure was a result of direct fuzzification of the INEP algorithm (Fuzzy-INEP model). In this way, the good behaviour of the original model can be kept, while introducing the advantages of the fuzzy logic. The structure is depicted in Fig. 2.6, a and is based on one fuzzy inference system with three input variables. The resulting rule base consists of 27 rules, created by the experts from the field of highway management and road safety (2.7, a).

The second approach depicted in Fig. 2.6, b is a hierarchical, two-level fuzzy model. In the first level, only two variables are evaluated, speed and flow. This first level cannot distinguish the cause for low traffic flow (low demand or too high demand according to the fundamental diagram). This is the reason for the second level, where the density is used to adjust the result according to the traffic situation (high and low density). This proposal significantly simplifies the model structure and the size of the rule base (Fig. 2.7, b and c).

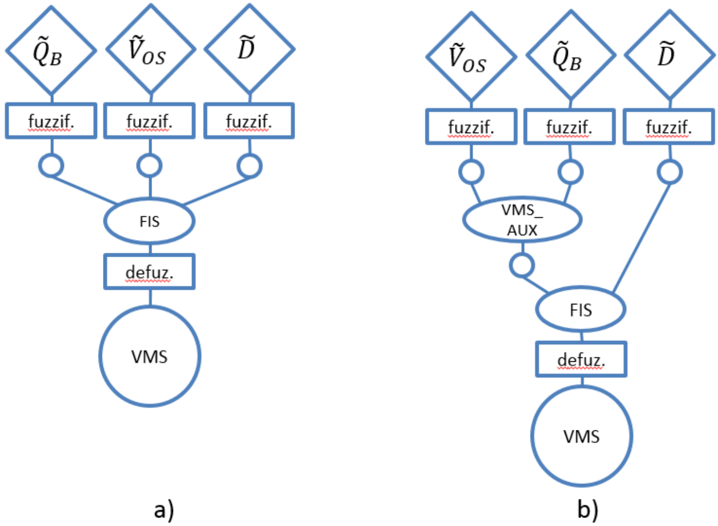


Figure 2.6: Different evaluated structures of the proposed fuzzy models: a) Fuzzy-INEP model and b) hierarchical two-level model

3. Different types of hysteresis

While in the decision tree based algorithm, the oscillation (i.e. frequent changes of the imposed speed limit) was minimized through in-built hysteresis (different parameters to turn on and off certain speed limit), the fuzzy logic based algorithms have to deal with the problem in a different way. Actually, three different approaches were evaluated.

The first one dealt with the smoothing of the input variables. Different values of the smoothing factor in the exponential smoothing were tested. This can be however only partially successfully, as the smoothing introduces also delay, which is hardly acceptable for the implementation.

Next, the assignment of the particular speed limit based on the defuzzified output (in general any number in the range from 60 to 130 km/h) of the algorithm was used. The algorithms were tested in different configurations $H*$ denoting how much the target value must be exceeded in order to switch on a speed limit. For example, $H0$ in the description of the algorithm means that the output 80 km/h

Speed (V)	Density (D)	Flow (Q)	Speed limit [km/h]
High	Small	Small	**130**
High	Small	Medium	**130**
High	Small	High	**120**
High	Medium	Small	**80**
High	Medium	Medium	**120**
High	Medium	High	**100**
High	High	Small	**80**
High	High	Medium	**80**
High	High	High	**80**
Medium	Small	Small	**130**
Medium	Small	Medium	**120**
Medium	Small	High	**100**
Medium	Medium	Small	**100**
Medium	Medium	Medium	**100**
Medium	Medium	High	**80**
Medium	High	Small	**80**
Medium	High	Medium	**80**
Medium	High	High	**80**
...			

a)

Speed (V)	Flow (Q)	VMS_Aux
High	Small	**140**
High	High	**120**
Small	Small	**80**
Small	High	**60**

b)

VMS_Aux	Density (D)	Speed limit [km/h]
Small	Small	**140**
Small	Medium	**80**
Small	High	**60**
High	Small	**140**
High	Medium	**100**
High	High	**80**

c)

Figure 2.7: Fuzzy rules for a) Fuzzy-INEP model and b) the first and c) second level of the hierarchical model

switches on the VSL sign 80 km/h (with the speed limit 60km/h active), but the algorithm denoted $H5$ needs a value of at least 85 km/h.

The third approach includes a memory and a penalization of frequent changes of the imposed speed limit. If the algorithm changed in the previous W steps, the repeated change is not recommended.

In all cases, the hysteresis is applied only to increase the speed limits. The speed limit lowering is executed immediately when the need is identified, otherwise there is a negative impact on the traffic safety.

Based on such different settings, a rather large set of fuzzy logic–based control algorithms was defined and evaluated.

3 Evaluation of the implemented highway management system

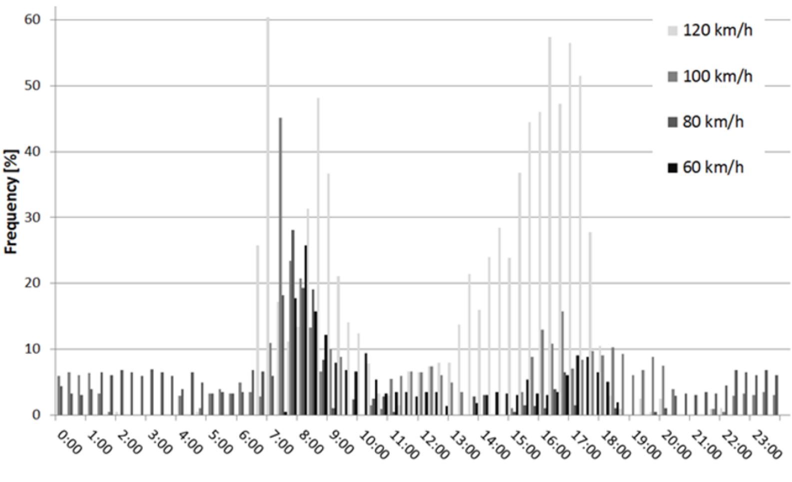
In the previous chapters, different algorithms for speed harmonization designed during the research projects were briefly described. One of the important remaining tasks was to evaluate their impact. There are clearly different impacts of such system, such as improvements of capacity of the road or improvement of safety due to harmonized speed. At the same time, even though several researchers focused on definition of a general objective function, its usage is at least questionable (Maier and Grötsch, 2016). For this reason, in this work we do not propose a joint objective function, but rather focus on particular aspects separately. Our focus is on the impact of VSL on selected traffic flow parameters, even though the impact on the speed harmonization will be discussed as well.

The evaluation was conducted in several steps. The traffic on the Prague city ring and the control algorithms were modelled in microscopic simulation models using data from real traffic sensors. It introduces several advantages; it is possible to test different scenarios, it is possible to set any number of virtual traffic sensors to collect data and to observe and measure particular traffic situations. Since the decision tree-based algorithm was really implemented on the Prague city ring, the data collected there were used to study its real effect on the traffic flow. Additionally, the compliance of the drivers to the imposed speed limits is presented as well.

3.1 Descriptive statistics of the speed harmonization algorithm

For demonstration purposes, a section of the Prague city ring between highway D5 and the entry point to the Lochkov tunnel (km 21,8 – km 14,5 in the direction Brno, where 6 gantries with VMS are installed) is evaluated in this chapter. This section is suitable due to its relatively high traffic volume (up to 67000 vehicles per day in both directions). The data for evaluation are from October 2012, since such month is not influenced by holidays or extreme weather conditions and its traffic characteristics correspond to the yearly average. Traffic data were available at tree minute sampling interval.

The peak traffic flow in this location is about 4000 veh/h and average speed in this location is due to the traffic bottleneck caused by the exit 16 as low as 60 km/h. Fig. 3.1 depicts the average frequency of imposing the particular speed limits (60 km/h up to 120 km/h) in this location during different parts of day.



a)

Active VSL	without VSL	120 km/h	100 km/h	80 km/h	60 km/h
Frequency [%]	75,73	11,95	5,52	4,08	2,72

b)

Figure 3.1: The frequency of particular speed limits during different parts of day (a), and the overall daily aggregation (b) (Beneš and O. Přibyl, 2014)

As depicted in the frequency histogram of the VSL activity, during the period before 7 am there was regular reduction of speed limits, which lasted until about 8 am, when rush hour culminated. In about

20 % of the cases at this time, the lowest speed limit, 60 km/h, was activated. After that, the traffic conditions started to stabilize and from circa 9:30 am, no VSLs were typically applied. A similar situation was during the afternoon rush hours, however the flow was not typically as high as in the morning and therefore the control system usually reacted with limitation to only 120 km/h.

During the off-peak hours, the VSLs were usually not applied. The seldom speed restrictions during this time (especially at night) were activated due to weather conditions, such as heavy fog or other events like stationary vehicle on the road.

3.2 Microscopic-based simulation of traffic

Within the INEP project, the model was implemented in the microsimulation software (Chang, Wang, and Ioannou, 2007; O. Přibyl, 2007b) from the company PTV, Vissim, within the project SIRID, a tool from the company TSS, AIMSUN, was used. There were different reasons for choosing different simulation tools. The most important one was dealing with the interfaces on the tools. While in INEP, the authors developed and published a new approach to implement fuzzy control directly in the simulation models (Koukol and O. Přibyl, 2013), in the project SIRID, an interface between AIMSUN and MATLAB (as well as real highway system for the purpose of technology evaluation) was implemented to allow for better exchange of data and more flexible control algorithms. The principal scheme of the communication module is provided in Fig. 3.2.

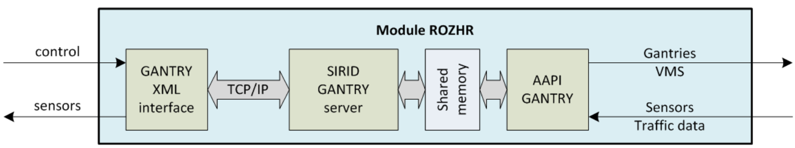


Figure 3.2: Communication interface implemented as part of the SIRID project

Significant effort was dedicated to the calibration of the microscopic simulation. In order to evaluate the speed harmonization algorithms, the effect of so-called Stop & Go waves (Kerner, 2004) must be incorporated in the model. This was rather complex task, where different parameters of the model were tuned until satisfactory results were obtained. The simulation proved that the proposed VMS means a significant improvement to the traffic conditions on the Prague city ring. This can be demonstrated when comparing the situation without any control and with implemented INEP algorithm for example on the average density (Fig. 3.3) and average delay (Fig. 3.4). The darker colours in the density diagram during the morning peak hours clearly depict the increase of density and thus increase in the throughput. This is confirmed also by the average delay that was also during the morning peak hours significantly reduced. This is an important result clearly demonstrating the positive effect of the VSL system and the speed harmonization effect.

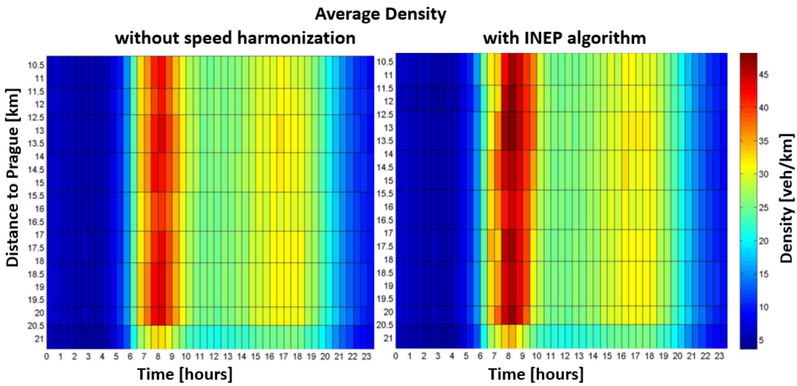


Figure 3.3: Average simulated density for a situation without control and with implemented INEP control algorithm

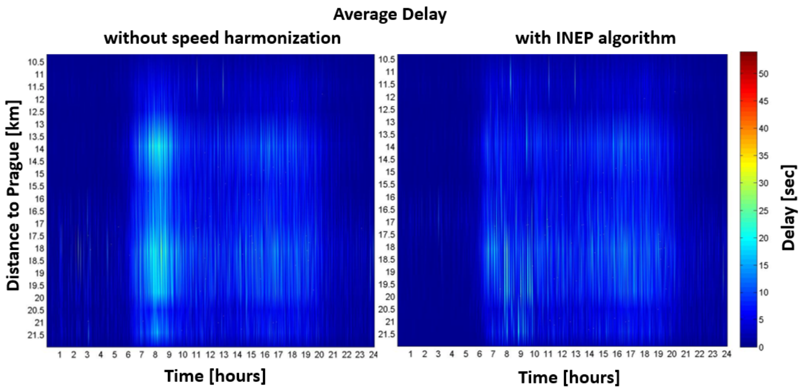


Figure 3.4: Average simulated delay for a situation without control and with implemented INEP control algorithm

Fig. 3.5 focuses in more details on the comparison of the different fuzzy-logic based algorithms. It is an example comparing average flow and density for selected algorithms with respect to the situation without control on the 17,0 km (the naming of the algorithms is based on their type together with used hysteresis algorithm and the level of smoothing – for more details, please refer to the research report for project TAČR – SIRID, 2014). The figure shows that there is an increase of 16,6% on the average density for the fuzzy-logic based algorithm ($F2H0h-6$) when compared to the situation without any control.

We can see that the peaks of the speeds (after 7.4 resp. 7.6 time value in the figure) are smoothed, which is the desired effect of speed harmonisation. The fuzzy-logic based algorithm is switched on earlier (quick reaction time) and it has better effect on the harmonisation.

Apart from the global parameters such as average density, we can also look in more details into the effect on speed harmonization. The resulting speed limits for the INEP algorithm and a fuzzy-logic based algorithm together with the measured speeds are provided in Fig. 3.6.

Algorithm	Changes in flow	Changes in average speed	Changes in average density
INEP	2,5%	-8,6%	11,6%
F1H0h-3	2,4%	-8,5%	10,3%
F1H5h-3	1,2%	-8,2%	10,0%
F1H0h-6	3,8%	-9,9%	13,3%
F2H0h-3	1,9%	-8,8%	10,0%
F2H5h-3	3,5%	-9,7%	12,0%
F2H0h-6	3,6%	-10,2%	13,6%
F3H0h-3	2,5%	-8,8%	10,7%
F3H0h-6	3,3%	-9,5%	11,5%
F3H5h-3	3,1%	-9,4%	12,1%

Figure 3.5: Changes (in percent) of average flow and density for selected algorithms compared to the situation without any control

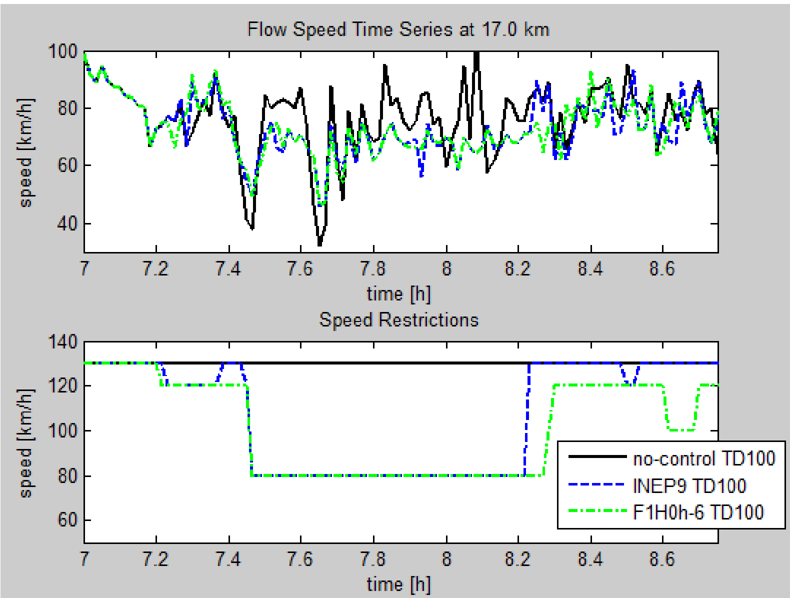


Figure 3.6: Comparison of the INEP algorithm and an algorithm based on fuzzy logic denoted F1H0h-6 TD100

3.3 Results from the Prague city ring

In the introductory part, the fundamental diagram was introduced as a way to describe traffic flow characteristics. In this chapter, we use and further describe the principles to demonstrate the effect of a variable speed limit system on the traffic flow. An example of fundamental diagrams is shown in Fig. 1.2. The point denoted by the road capacity q_m, the critical density k_m, and the optimal speed v_m describes so-called point of stability that clearly splits the fundamental diagrams into areas with stable, resp. unstable traffic conditions. Literature as well as practical experiments have shown that the critical values may not be constant and they can vary under different weather conditions, however it is possible to use them to generally describe the traffic flow behaviour (Papageorgiou, 1984).

3.3.1 VSL evaluation using fundamental diagram

Several authors investigated the impact of VSL on the fundamental diagram. Zackor, 1991 demonstrated that speed harmonization (i.e. effect of VSL) increases capacity as well as average speed by about 5 % to 10 %. This trend, split for particular speed limits was presented by Cremer, 1979 and is depicted in Fig. 3.7. The term b is the ratio of the applied VSL divided by the speed of free flow, where $b = 1$ corresponds to the VSL limit equal to the speed of undisturbed traffic flow.

Our aim was to verify, whether similar result were achieved on the Prague city ring after the speed harmonisation system was implemented. In order to verify this VSL-induced fundamental diagram change for the situation in the Prague city ring, the Fig. 3.8 is presented. It depicts the data from the 18,7 km gantry on October 2012. Each point here corresponds to a 3-minute aggregation of the measured flow-occupancy data. Its type (shape and shade) denotes the imposed speed limit at that time. A curve was fitted to all the data for each of the different speed limits.

The full line in Fig. 3.8 corresponds to the situation with no VSL. It is obvious that the measured data are available for the stable part of the diagram only. This actually demonstrates proper functionality of the control system, since VSL is imposed when leaving this stable part and thus no data are available for the unstable area.

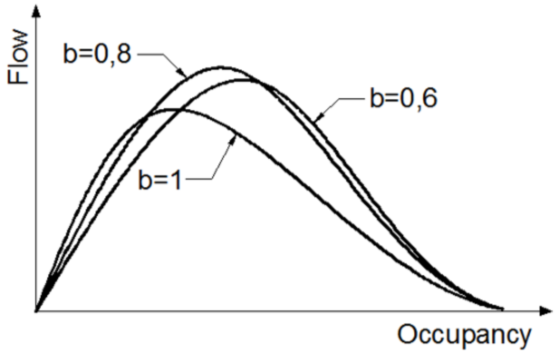


Figure 3.7: Theoretical traffic characteristics for different speed limits (source: Cremer, 1979)

The dashed line in Fig. 3.8 corresponds to the situation where $b = 1$ in Fig. 3.7, i.e. situation with the speed limit equal to the speed of free flow which is about 120 km/h. This line also has the highest slope. The reason why this is by speed limit of 120 km/h and not the situation with no speed limit (i.e. the default maximal speed limit on highways, 130 km/h) is in the authors opinion due to the fact that b is almost equal to 1, but at the same time is the speed already more harmonized due the the increased drivers' alertness.

The highest capacity was achieved in a situation with VSL equal approximately $0,8$ of the free flow speed, i.e. 100 km/h (point A in the figure). With lower VSL, the critical occupancy is increased (shift of the peak to the right); however, the maximal flow is decreased.

This is an important finding since the functionality of the VSL is confirmed.

3.3.2 Impact of VSL in time space diagram

A VSL system is of course more complex and the coordination between particular gantries is critical. The algorithms are based not only on the local measurements, but also on measurements from other locations. To display these spatio-temporal relations, so-called space-time contour plot can be used as in Fig. 3.9 (Bertini, Boice, and Bogenberger, 2006). The time is displayed on the x-axis, and the position of each gantry on the y-axis. The mean speed of the vehicles

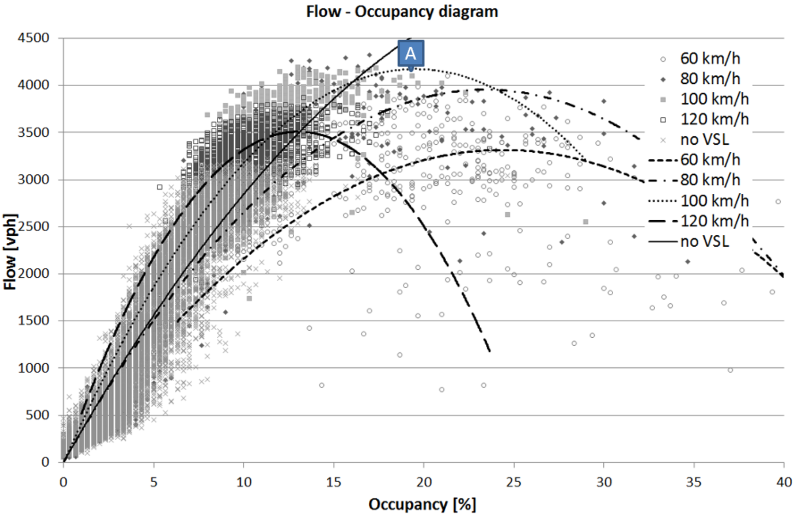


Figure 3.8: Flow - Occupancy diagram together with the interpolated functions for particular speed limits based on data from October 2012 (source: Beneš and O. Přibyl, 2014)

(at three minutes samples) is shown by the different colours, where lower mean speed is represented by red colour and higher values of speed are represented by darker colours (blue). The VSL is displayed in the same diagram with the usage of symbols at each gantry.

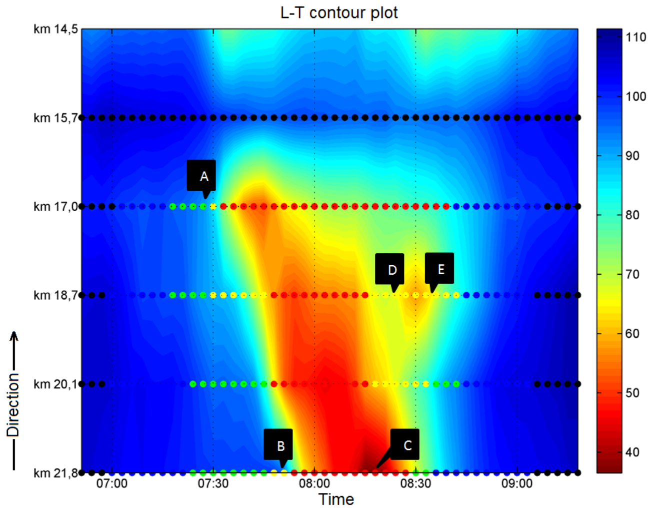


Figure 3.9: Space-time diagram of the average speed. The coloured dots depict the different imposed VSL: black – no VSL; blue – 120 km/h; green – 100 km/h; yellow – 80 km/h; and red – 60 km/h) (source: Beneš and O. Přibyl, 2014)

The figure describes a situation from the 9th of October, 2012. The mean speed of the vehicles began to diminish as the density of traffic flow increased at 7:25 am between gantries at km 17,0 and km 15,7 (marker A). Here a bottleneck forming by Exit 16 is located. After 7:30 am, the traffic congestion occurred at the bottleneck and then propagated upstream to Exit 23 (near which last gantry on km 21,8 is located). Speed of the spreading of the congestion was about -12 km/h and at the gantry on km 21,8 was the congestion observed at about 7:51 am (marker B). In contrast, the speed of the imposing of VSL was faster (from the perspective of upstream spreading) about - 16 km/h. This faster activation of VSL decreased the differences between speed of vehicles on the tail of congestion and speed of vehicles which were still moving in relatively free traffic conditions. The lower speed differences significantly increase safety and also precede further spreading of the congestion. This was evaluated also with the usage of simulation, where much worst situation was observed in case of no VSL.

The fact is that is basically impossible to systematically prevent occurrence of the traffic jam if intensity of traffic flow is very high, but due to the VSL system, the impact of the traffic jam is mitigated and even at Exit 23, where traffic congestion a speed drop culminated at 8:18 am (marker C), the mean speed of the vehicles was still over 35 km/h.

At 8:25 am on the gantry km 18,7, another small mean speed drop was observed, but likely due to the VSL system wasn't spread further and at 8:36 am (marker E) the traffic conditions was stabilized in spite of the lasting high intensity of traffic flow (3500-4000 veh/h). This clearly demonstrates the positive effect of the cooperative behaviour of the VSL and its effect on the traffic flow.

3.4 Study of driver's compliance

The positive effects of VSL systems can be achieved only when drivers adjust their speed to the imposed speed limits. Unfortunately, not all drivers follow the speed limits. The level of compliance for the newly implemented VSL system on the Prague city ring had not been known. It also cannot be simply adopted from abroad as it is affected by several aspects, such as level of enforcement, trust in the highway management system, the geographical region or cultural habits. In order to gain more insight into the topic of drivers' compliance, the author analysed data from the highway management system on the Prague city ring.

Data collected from the Prague city ring were pre-processed and categorized into several groups according to the different driving conditions. It was important to determine whether drivers react truly to the changes in VSL system or whether the change in their behaviour is a result of the adjacent traffic due to increased traffic density. The data contain information about the behaviour of drivers during the period of VSL system activation, as well as their behaviour 20 minutes before and after VSL activation. Data about vehicle counts and speeds that were not influenced by any limits were used as control group.

Fig. 3.10 illustrates a typical situation – the aggregated behaviour of the drivers within the first minutes after a speed limit of 100 km/h is imposed during morning hours. There is no significant visible decrease in the measured speeds due to the VSL. This was also the first impulse to analyse the data in more details.

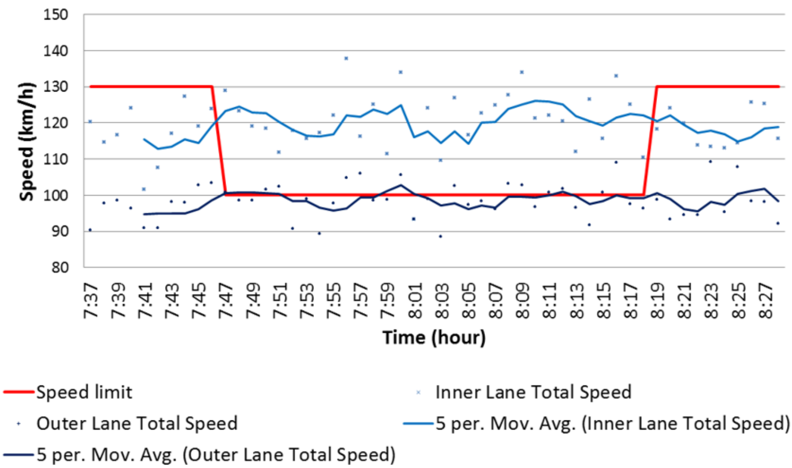


Figure 3.10: Speed diagram presenting average speed of vehicles on two lines and imposed VSL

In order to do that, we looked at the main statistical values (average speeds and standard deviations for different speed limits within each category). Surprisingly, the results indicate that imposing the speed limit of 120 km/h leads for the fast as well as slow lane to an increase in the measured average speeds (increase from 112.21 km/h to 113.16 km/h for the fast lane, resp. from 94.49 km/h to 98.05 km/h for the slow lane). This behaviour could be caused by the migration of faster travelling drivers from left lane to the right lane after implementation of new speed limit. These drivers slow down, but still increase the average speed in the right lane. The fewer drivers in the left lane are not limited by other drivers and can increase their speed.

The main expected effect of VMS is however in harmonization of speed. This means, that even when the average value is higher, the standard deviation of speeds should be decreased (vehicles should be driving at similar speeds due to the VMS). The results presented in Fig. 3.11 however demonstrate that when imposing the speed limit of 120 km/h during the day, the standard deviation of speed increases from 8.56 km/h to 10.72 km/h for the left line and from 6.16 km/h to 6.77 km/h for the right line. These results suggest that if the drivers are not influenced by adjacent traffic, VMS actually leads to reduction of speed harmonization.

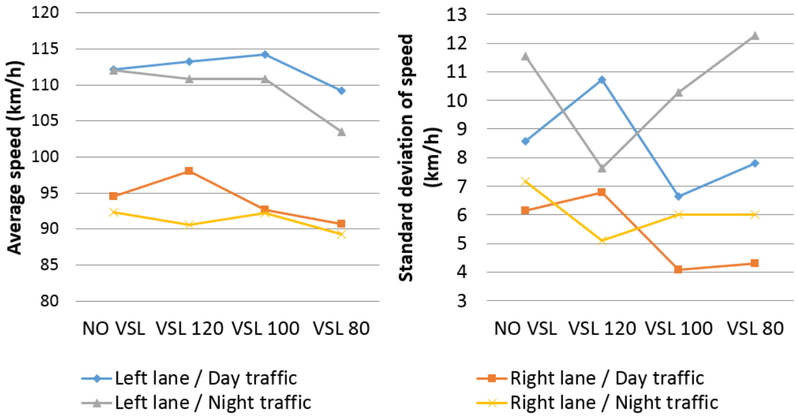


Figure 3.11: Average speed and standard deviation of speed for low traffic and different speed limits

In order to justify these visual findings, a statistical hypothesis testing was used. Hypothesis testing is a systematic way to test claims about a sample and the population. An independent sample z-test (Privitera, 2015) was used and the following two hypotheses were stated:

H0: The VSL system does not influence the average driving speeds.
H1: The VSL system influences the average driving speeds.

The level of significance was set at 5 %. The power or sensitivity was calculated for analysed data at level of over 0.95 for each examined case. To determine the likelihood of measuring the tested sample out of investigated population, the z-test statistics is used.The results are displayed in Fig. 3.12, where "Z value" represents the value for z-test (distance expressed by number of standard deviations from mean value), and P values represents the probability for occurring such result in the examined population for 2 tailed and 1 tailed test accordingly. When the P value is less than 0.05, we reach significance (i.e. the decision is to reject the null hypothesis).

The results in Fig. 3.12 show that we have not reached significance and are not able to reject the null hypothesis $H0$ in any of the cases under observation. This is true for 2-tailed as well as 1-tailed tests. Please note that for some speed limits, there was not sufficient number of samples and for this reason are the field filled with the value N/A. This can be caused by the fact that the defensive drivers that are more willing to obey traffic rules, do slow down and move to the right traffic lane. In consequence of this action, speed variance in both lanes is actually increased due to new vehicles that have just started to adjust their speed, and at inner line aggressive, fast drivers see chance to go even faster than they did before as lane has less obstacles now in front of them. This behaviour cannot be confirmed during night hours as drivers traveling at worse visual conditions tend to lose their confidence and are more likely to adjust their speed according to the speed limits.

Large contribution to the decrease of speed variance at 100 km/h during the night hours is due to the higher number of truck drivers. This was not further analysed within the hypothesis testing, but the number of trucks increases from average of 25.4% during the day to 38.9% in the night hours. In case the VSL is equal to 100 km/h, the trucks driving at about the same speed actually improve the perception of the traffic flow.

For the category speed limit equal to 80 km/h we can observe no significant change of speed standard deviations during the day hours, but for night hours there is an increase visible. This may be caused by the truck drivers mentioned above, but also may be simply observed by personal car drivers as to low limit to obey within low traffic at night conditions and without any participation.

Such conclusions are rather alarming, but cannot be simply generalized. One of reasons for the results obtained for the data from the Prague city ring is the absence of any automated enforcement system. Such system together with better marketing and educational campaign could increase drivers' reliance on the systems which would improve their compliance. This is for example a common practice on highways in Germany and it has a positive effect on the compliance of drivers. Situation as it is now causes some drivers to disobey implemented speed limitations and thus continuing travelling with higher speed. Another aspect that needs to be considered is the cultural and social influence on the drivers' behaviour.

	Left Lane			
Speed limit	NO VSL	VSL 120	VSL 100	VSL 80
Number of samples	1259	186	15	690
Left lane / Day	112,2	113,2	114,2	109,2
St. dev. of speeds	8,56	10,72	6,64	7,81
Z value	-	-0,09	N/A	-0,38
P - 2 tailed	-	0,93	N/A	0,70
P - 1 tailed	-	0,82	N/A	0,35

	Right Lane			
Speed limit	NO VSL	VSL 120	VSL 100	VSL 80
Number of samples	3643	1157	47	2140
Right lane / Day	94,5	98	92,7	90,7
St. dev. of speeds	6,16	6,77	4,09	4,29
Z value	-	-0,53	N/A	-0,89
P - 2 tailed	-	0,60	N/A	0,37
P - 1 tailed	-	0,30	N/A	0,19

Figure 3.12: Results of hypothesis testing (day traffic only)

4 Conclusions and next steps

This work focuses on an important topic – decreasing congestions and improving road safety on highways. This is not only an actual topic; it will have certainly even bigger influence in the future. Fig. 4.1 summarises predictions demonstrating clear increase in the cost of congestion (in millions of US Dollars) in different countries.

Country	Sector	2013	2020	2030	2013-30 % change
Germany	Direct costs (value of fuel and time wasted)	21,68	24,22	27,7	28
	Indirect costs (indirect costs of duing business)	11,79	13,12	16,14	37
	Total	**33,48**	**37,34**	**43,84**	**31**
USA	Direct costs (value of fuel and time wasted)	78,52	97,1	120,7	54
	Indirect costs (indirect costs of duing business)	45,34	54,16	65,53	44
	Total	**124,16**	**151,28**	**186,22**	**50**

Figure 4.1: Country level economy-wide direct and indirect costs, millions of US Dollars (adopted from CEBR 2014, accessed online: `http://inrix.com/wp-content/uploads/2015/08/Whitepaper_Cebr-Cost-of-Congestion.pdf`

In this work, the author demonstrated that a highway management system (HMS) has a positive impact on traffic flow parameters and through speed harmonization also on traffic safety. For this reason, HMS will be certainly one of the important measures in the future. Especially with the growth of car-to-car and car-to-infrastructure communication (generally denoted C2X), such system will be able to effect traffic even more directly. As we are aware of this fact, the research at the Czech technical university in Prague will continue by the author of this work. There are several principal areas under investigation.

Drivers' compliance is the subject of a research on a driving simulator. Here an experiment has been designed in order to measure not only aggregated behaviour through the traffic stream characteristics, but the behaviour of particular drivers in different traffic situations. At this moment, the experiment is being conducted and data needed for probabilistic regression models collected. The results should help us to model and understand how drivers with different socio-demographic characteristics react to the variable speed limits (VSL).

Also, a **third generation of the speed harmonization algorithms** based on distributed intelligence is being designed. Using multi-agent systems has several potential advantages. They are exploring the distributed nature of the control problem (distributed detectors as well as VMS, heterogeneous entities such as traffic sensors, weather sensors, different strategies, and others). They are also directly suitable for the modular architectural concept where the different agents have different role in the modular architecture (see Fig. 2.2). The system can be automatically extended into new regions without the need for a redesign/recalibration of the control algorithms. Last but not least, the system based on distributed intelligence can easily adopt new class of agents, such as individual vehicles. This is an important enhancement to incorporate and use the car to infrastructure (C2I) communication.

Based on the existing work, the author presents several recommendations:

1. Highway management system is an important system with a positive effect on road safety, economy and ecology. It is recommended to continue building HMSs in the Czech Republic.

2. Any new highway management system shall have a modular architecture in order to allow for easy implementation of new, advanced traffic control algorithms and strategies.

3. In order to increase the drivers' compliance to the VSL, at least the two following strategies shall be part of any solution:

    (a) Better informing of drivers about the positive effect of VSL. Negative marketing leads to lower acceptance of the speed limits und thus to decreased performance of the system. The drivers shall understand the benefits they gain when a HMS is implemented.

(b) Speed enforcement shall be integrated as part of the HMS solution. This approach has been successfully implemented in Germany (random enforcement) and the divers' compliance in Germany is significantly higher.

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Curriculum Vitae

Doc. Ing. Ondřej Přibyl, Ph.D., vice dean for international relations at the Faculty of Transportation Sciences, Czech Technical University (CTU) in Prague, got his Master degree at the Faculty of Electrical Engineering, CTU, in the area of technical cybernetics. He graduated at the PennState University in the USA in the field of transportation planning. Since 2003 he has been working as an assistant/associate professor at the Faculty of Transportation Sciences (FTS). Since 2013, he has been the Deputy Head of the Department of Applied Mathematics at FTS. He has also been working as a system architect and requirements manager in a German company JENOPTIK Robot for the past 10 years. Since 2016 he is the Head of Branch Office of the company JENOPTIK Robot GmbH – branch Prague.

His professional interest is in diverse fields, among others system theory, intelligent transportation systems, smart cities, mathematical modelling, data collection and analysis, or artificial intelligence. Lately, the major application field is Highway Management and Control as well as Smart Cities where he aims at using methods from the field of soft computing.

He has been a member of several professional organizations, such as Transportation Research Board. Young Member of the Committee on Travel Behaviour and Values, A1C04 (TRB, the National Academy of Sciences, USA); Member of Penn State ITS America Student Chapter; Young Member of the Committee on Travel Behaviour and Values, A1C04 (TRB, the National Academy of Sciences, USA); Gestor for standardization committee CEN/TC 278 Working Group 5 - Detection on Motorways for Traffic Information and Traffic Management Applications. He has reviewed over 40 papers for different journals and conferences including Transportation Research Board.

He received international certifications in diverse management and professional areas, such as Agile Scrum Master (2016), OMG-

Certified Expert in BPM (2012), CPRE: Certified Professional for Requirements Engineering (2011) or ITIL® version 3 Foundation Examination (2011). Selected publications from the last years cover among others:

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