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Effects of highway management on traffic flow characteristics

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ABSTRACT

Traffic telematics systems have been used to increase road capacity as well as safety. On highways, this is accomplished with the usage of so called highway management systems, which among others through speed harmonization, ramp metering, informing about weather conditions or danger on road addresses these issues. Such system was recently implemented for the first time also in the Czech Republic. In this paper, the results from the first months of operation will be provided. First, the expected theoretical effects of such system on traffic flow characteristics will be provided and discussed. These effects follow the theoretical foundations of traffic flow theory, represented for example by fundamental diagram or changes to road capacity due to speed harmonization. Based on the measured data, the results of the particular implementation in the city of Prague, Czech Republic will be provided. The results will be discussed and compared to international experiences.

KEYWORDS: highway management, fundamental diagram, highway capacity

1. Highway management and its implementation in Prague

This paper provides an overview of the highway management system in Prague. Its major objective is however to demonstrate its function by presenting and discussing the real results from the first years of operation. These results are put into theoretical context.

It has the following structure. After this introduction a short description of the highway management system installed on the Prague city ring is provided. Our focus is on the speed harmonization algorithm acting through variable speed limits (VSL) as the integral part of the HMS. Next, the theoretical foundations for evaluation of a highway management system together with results from the described system are provided and discussed. In the conclusion, the planned enhancements of the HMS in Prague are shortly introduced as well.

1.1 Overview of highway management system strategies

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 kilometers travelled are increasing continuously, it is not possible to keep increasing the road capacity by simple adding new roads. Additional measures, typically from the ITS field have to be introduced. And that is the case of highway management systems. HMS are typically addressing one or more of the following objectives:

1. Decrease of the number and impact of regular congestions
2. Decrease of the number and impact of irregular congestions
3. Increase of traffic safety

There are many different control strategies that can be used. Overview of strategies addressing these objectives adopted from [1] is provided in the Fig. 1. In this reference, detailed description and examples of the particular strategies is to be found as well.

The highway management strategies are facing a big growth, especially in the Czech Republic, where they are not in wide use yet. This is also due to the fact, that many international studies demonstrate their impact on road safety as well as ecology and economy. Some results from a study summarizing results from many international projects include [2]:

- Decreased travel time by 20% to 48%

- Decreased time to clear a traffic accident on average by 23 minutes (corresponds to 50%)
- Increased highway capacity by 17% to 25%
- Such promising results also increase the popularity of highway management systems. In this paper we aim to verify such strong statements and study the real effect for the first implementation in the Czech Republic.

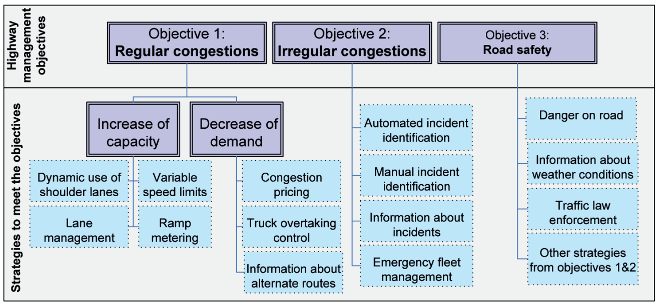

Fig. 1. Major highway management strategies. [own study based on 1]

1.2 Highway management system on the Prague city ring

In the Czech Republic, the first highway management system was put into operation in October 2010. This system was the output of a research project called INEP (Technological Agency of the Czech Republic) conducted in cooperation between company ELTODO a.s. and the Czech Technical University in Prague. Within this project, a modular framework based on the robust and well described German HMS [3] was developed. Modularity was really the key concept used within this project. Each management strategy is performed by a dedicated module and the particular results are then harmonized with each other as well as other control segments. The speed harmonization strategy is implemented as a rule-based system, which based on intensity (veh/h), local density (veh/km) and speed (km/h) determines the optimal control decision - the speed limit. Within the INEP project, the system was configured and evaluated using microsimulation model VISSIM. The simulation proved, that the proposed HMS means a significant improvement to the traffic conditions on the Prague city ring. This can be demonstrated for example on the average delay in the system, as presented in Fig. 2. The lighter colours mean larger overall delay. For the system with speed control (the right-hand image) the delay is significantly reduced.

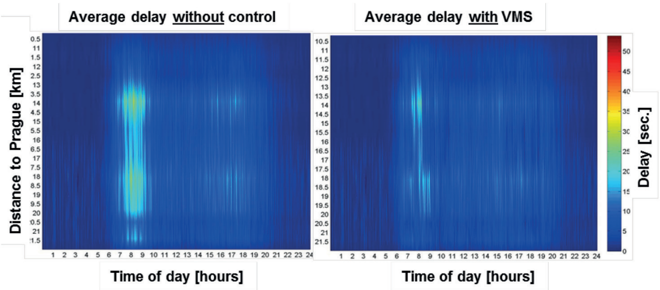

Fig. 2. Travel delay as a result of the simulation of the uncontrolled situation (left) and with the speed harmonization (right) [own study]

Currently, another research project (SIRID) is aiming at the development of a second and improved generation of the HMS. As part of these improvements, a detailed analysis of the implemented solution will be provided. This paper aims to provide such results and together with more detailed analysis. The authors hope it will contribute to the general awareness of HMS and their positive influence on traffic.

2. Evaluation of the speed harmonization algorithms

Speed harmonization aims mostly on improvements of safety. This is however more difficult to demonstrate and it is typically measured in a long term or estimated as a function of other traffic parameters, for example speed deviations ([4], [5]). This effect is however rather straightforward (smaller differences in speed clearly positively influence the danger of an accident). In this paper we focus on the effect of speed harmonization on the traffic parameters.

2.1 Statistical evaluation of the existing traffic situation and control

Within this paper, 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 HMS are installed will be evaluated. This section is suitable due to its relatively high traffic volume (up to 67000 vehicle s per day). 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. These aggregations were also used in the VSL control algorithms.

All presented values (if not stated otherwise) are average values from the October 2012. 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 depicts the frequency of particular VSL in this location during different parts of day.

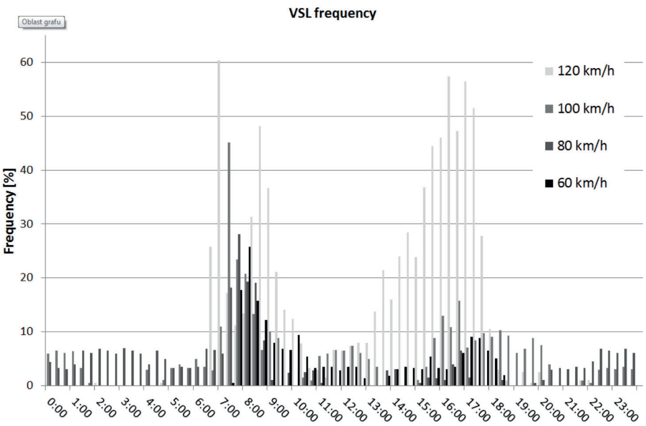

Fig. 3a. The frequency of particular speed limits during different parts of day [own study]

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

Fig. 3b. The frequency of particular speed limits during overall daily aggregation [own study]

As depicted in the frequency histogram of the VSL activity in 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 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 VSL 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 VSL 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 etc.

2.2 Fundamental diagram analysis

Since no traffic data are available from the period before launching the HMS (the entire highway system was built at the same time as the HMS), the before-after analysis could not be performed in our case. Therefore an evaluation of the fundamental diagram was used within this paper to proof the influence of the VSL on the traffic flow.

The fundamental diagram is basically a display of the main traffic flow variables (usually flow-occupancy or speed-flow) in a graph. In such diagrams, we can easily find areas where the traffic conditions are still stable and at which point the traffic congestions begin to occur. An example of fundamental diagrams is shown at Fig. 4. The variable Q_{max} denotes the critical flow, O_C denotes the critical occupancy, and V_C is the critical speed. Together they describe the position of the point of stability and value of road capacity, which is located on the peak of the curve.

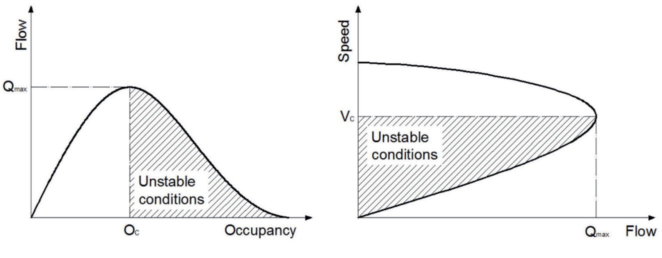

Fig. 4. Fundamental diagram and stability [own study based on 6]

In the flow-occupancy diagram, the maximal throughput of the road Q_{max} (road capacity) is reached when the occupancy equals the critical occupancy O_C. In the speed-flow diagram, the value V_C is the speed of traffic flow at which the maximal throughput is achieved. Slope of the line that connects the particular point on the traffic condition curve with the origin in the flow-occupancy diagram gives the mean speed of that traffic flow. The critical values may not be constant and they can vary under different weather conditions, however it is possible to generally describe the traffic flow behaviour with them [6].

2.2.1. VSL evaluation using fundamental diagram

Speed harmonization (i.e. effect of VSL) increases capacity as well as average speed by about 5 % to 10 % [7]. This trend, split for particular speed limits was presented in [8] and is depicted in Fig. 5. 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.

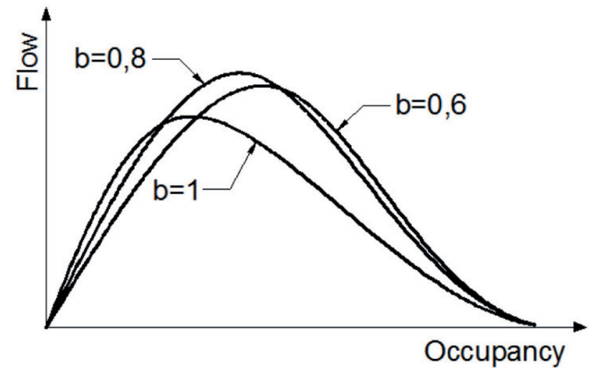

Fig. 5. Theoretical traffic characteristics for different speed limits [8]

In order to verify this VSL-induced fundamental diagram change for the situation in the Prague city ring, the Fig. 6 is presented. It depicts the data from October 2012, the 18,7 km gantry on highway R1. Each point here corresponds to a 3-minute aggregation of the measured occupancy-intensity data. Its type denotes the imposed speed limit at that time. For each of the different speed limits, a curve was fitted to all the data.

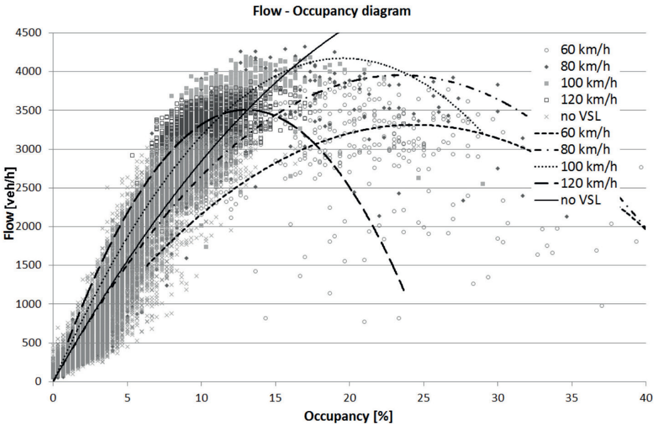

Fig. 6. Flow - Occupancy diagram together with the interpolated functions for particular speed limits based on data from October 2012 [own study]

The full line in Fig. 6 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 instable area.

The dashed line in Fig. 6 corresponds to the situation where in Fig. 5, i.e. situation with VSL equal to the speed of free flow which is about 120 km/h. Remark 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 VSL (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.

The highest capacity[1] would be reached in a situation with VSL equal approximately 0,8 of the free flow speed (100 km/h). With lower VSL, the critical occupancy is increased; however, the maximal capacity is decreased.

2.3 Impact of VSL in time and space

A VSL system is of course more complex and the coordination between particular gantries is critical. To display these spatiotemporal relations, the space-time contour plot shown in Fig. 7 [9]. The time is displayed on the x-axis, and the position of each gantry on the y-axis. The mean speed of the vehicles (at three minutes samples) is shown by the grayscale shades, where lower mean speed is represented by lighter shades and higher values of speed is represented by dark shades. The VSL is displayed in the same diagram with the usage of symbols at each gantry. The symbols and their corresponding meaning are as follows: Plus – no VSL; circle – 120 km/h; asterisk – 100 km/h; diamond – 80 km/h; and square – 60 km/h.

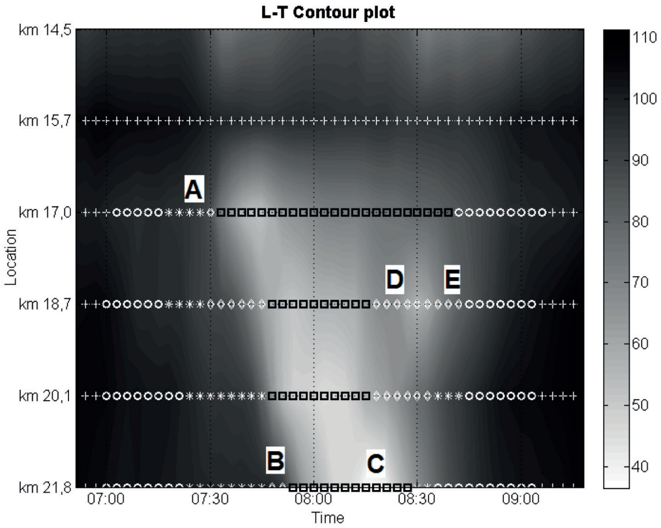

Fig. 7. LT diagram of the average speed. The symbols depict the different imposed VSL: Plus – no VSL; circle – 120 km/h; asterisk – 100 km/h; diamond – 80 km/h; and square – 60 km/h) [own study]

Fig. 7 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. Conclusion

This paper presented theoretical ways in which VMS affects main traffic characteristics. This was demonstrated within this paper with the help of a fundamental diagram as well as a time-space diagram. Next to the theoretical values, the results of the highway management system installed in the year 2010 on the Prague city ring were presented. It was demonstrated within this paper, that the system has the expected effect on traffic.

Highway management is however still an actual topic in the Czech Republic. At this moment a new research project aims to improve the algorithms used on the Prague city ring. The improvements are aiming, for example, at better processing of the measured data. Currently, data from three minute intervals are used for control. This sometimes leads to delays in the reaction times of the control system. Our trend is in using one minute time intervals together with better data pre-processing.

Additionally, new approaches will be used instead of the rule-based method currently implemented. The focus is in probabilistic reasoning (Bayesian networks) and on soft-computing methods, particularly algorithms based on fuzzy logic. Such approaches are also in literature acknowledged as a natural extension and improvement of the crisp control.

Before implementing the discussed changes, the new approaches will be evaluated with the help of microsimulation tools, as was done with the first generation of highway management. This allows us to do thorough before/after analysis of the traffic situation.

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[1] This fact was however later disputed for example by Smulders [10].

Acknowledgments

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