# PROCEEDINGS OF ELMAR-2018

60th International Symposium ELMAR-2018

16-19 September 2018, Zadar, Croatia

EDITED BY

***Mario Muštra***
***Mislav Grgić***
***Branka Zovko-Cihlar***
***Dijana Vitas***

University of Zagreb
Faculty of Electrical Engineering and Computing
Department of Wireless Communications
Unska 3 / XII
10000 Zagreb
CROATIA

| | |
|---|---|
| Published by: | Faculty of Electrical Engineering and Computing,<br>University of Zagreb |
| Edited by: | Mario Muštra, Mislav Grgić, Branka Zovko-Cihlar, Dijana Vitas |
| Front Cover: | Painting by artist Mrs Ljerka Njerš |
| Printed by: | LotusGRAF, Zagreb |
| ISBN: | 978-953-184-244-0 |
| ISSN: | 1334-2630 |
| IEEE Catalog Nr.: | CFP18825-PRT |

Printed in Croatia.

# 60th International Symposium ELMAR-2018 is organised by:

*Croatian Society Electronics in Marine - ELMAR, Zadar*

*University of Zagreb Faculty of Electrical Engineering and Computing,*
*Department of Wireless Communications*

**ELMAR-2018 takes place under the high patronage of the President of the Republic of Croatia,**
**Mrs. Kolinda Grabar-Kitarović**

## ELMAR-2018 symposium General Sponsor

***County of Zadar***

## ELMAR-2018 symposium Sponsors

*Ministry of the Sea, Transport and Infrastructure of*
*the Republic of Croatia*

*Ministry of Science and Education of the Republic of Croatia*

*Town of Zadar*

*OiV - Transmitters and Communications Ltd.*

*HRT - Croatian Radiotelevision*

*Croatian Regulatory Authority for Network Industries*

## ELMAR-2018 symposium takes place under the co-sponsorship of:

*IEEE Region 8*
*IEEE Croatia Section*
*IEEE Croatia Section Chapter of the Signal Processing Society*
*IEEE Croatia Section Chapter of the Antennas and Propagation Society*
*IEEE Croatia Section Chapter of the Microwave Theory and Techniques Society*
*Croatian Academy of Sciences and Arts*
*Croatian Academy of Engineering - HATZ*
*University of Zagreb*
*University of Zagreb Faculty of Electrical Engineering and Computing*
*University of Zadar*

## ELMAR-2018 symposium is supported by:

*ZADAR TOURIST BOARD*
*MARKOJA*
*OTP BANKA HRVATSKA*
*GRADSKA PLINARA ZAGREB*
*TEHNOZAVOD-MARUŠIĆ*
*FALKENSTEINER BORIK ZADAR CROATIA*

# ELMAR-2018 SYMPOSIUM COMMITTEES

## General Chair

*Branka Zovko-Cihlar*, University of Zagreb, Croatia

## Program Chair

*Mislav Grgić*, University of Zagreb, Croatia

# ELMAR-2018 SYMPOSIUM INTERNATIONAL PROGRAM COMMITTEE

*Juraj Bartolić*, Croatia
*Narcis Behlilović*, Bosnia and Herzegovina
*Aura Conci*, Brasil
*Marek Domanski*, Poland
*Janusz Filipiak*, Poland
*Borko Furht*, USA
*Mohammed Ghanbari*, United Kingdom
*Dušan Gleich*, Slovenia
*Mislav Grgić*, Croatia
*Sonja Grgić*, Croatia
*Ho Yo-Sung*, Korea
*Bernhard Hofmann-Wellenhof*, Austria
*Ebroul Izquierdo*, United Kingdom
*Ana Katalinić Mucalo*, Croatia
*Ismail Khalil*, Austria
*Tomislav Kos*, Croatia
*Igor Kuzle*, Croatia
*Panos Liatsis*, United Kingdom
*Lidija Mandić*, Croatia
*Branka Medved Rogina*, Croatia
*Borivoj Modlic*, Croatia
*Marta Mrak*, United Kingdom
*Mario Muštra*, Croatia
*Zdeněk Němec*, Slovak Republic
*Miloš Oravec*, Slovak Republic
*Jarmila Pavlovičova*, Slovak Republic
*Fernando Pereira*, Portugal
*Jan Pidanič*, Slovak Republic
*Peter Planinšič*, Slovenia
*Pavol Podhradský*, Slovak Republic
*Darko Ratkaj*, Switzerland
*Fabiana Rodrigues Leta*, Brasil
*Gregor Rozinaj*, Slovak Republic
*Markus Rupp*, Austria
*Gerald Schaefer*, United Kingdom
*Shiguang Shan*, China
*Thomas Sikora*, Germany
*Karolj Skala*, Croatia
*Ryszard Stasinski*, Poland
*Luis Torres*, Spain
*Frantisek Vejrazka*, Czech Republic
*Dijana Vitas*, Croatia
*Stamatis Voliotis*, Greece
*Krzysztof Wajda*, Poland
*Branka Zovko-Cihlar*, Croatia

# ELMAR-2018 SYMPOSIUM
# INTERNATIONAL REVIEW COMMITTEE

# ELMAR-2018 SYMPOSIUM
# ORGANISING COMMITTEE

# CROATIAN SOCIETY ELECTRONICS IN MARINE - ELMAR

President: *Branka Zovko-Cihlar*

Vice-president: *Ivan Pupovac*

Secretary: *Vladimir Roboz*

**Members of the ELMAR Executive Committee:**

*Winton Afrić, Irena Galić, Mislav Grgić, Sonja Grgić, Irena Jurdana, Branka Medved Rogina, Snježana Rimac-Drlje, Vladimir Roboz, Sonja Zentner Pilinsky*

**Members of the ELMAR Supervisory Committee:**

*Tomislav Kos, Boris Kviz, Lidija Mandić*

Address: Faculty of Electrical Engineering and Computing
Croatian Society Electronics in Marine - ELMAR
Unska 3 / XII, 10000 Zagreb, CROATIA

Phone: + 385 1 6129 567

Fax: + 385 1 6129 717

E-mail: elmar2018@fer.hr

URL: www.elmar-zadar.org

# Comparison of Controllers for Variable Speed Limit Using Realistic Traffic Scenarios

Edouard Ivanjko[1], Gabriel Oliveira Melo[2], Krešimir Kušić[1] and Martin Gregurić[1]
[1] Department of Intelligent Transport Systems, Faculty of Transport and Traffic Sciences, University of Zagreb, Croatia
[2] Department of Transport Engineering, Engineering school of São Carlos, University of São Paulo, Brazil
*edouard.ivanjko@fpz.hr*

***Abstract*—Urban motorways are designed to serve higher traffic loads but rush hours are causing periodically unstable traffic flows and congestions. Variable Speed Limit Control (VSLC) can alleviate congestion by posting appropriate speed limits on Variable Message Signs. In this paper, three controllers for VSLC are compared using a simulation model based on real traffic data obtained from the PeMS database collected at a selected motorway of the State of California, USA. The results show that the implemented VSLC controllers have the ability to improve the traffic condition in case of higher traffic intensity compared to an uncontrolled case.**

***Keywords*— Intelligent transport systems; Traffic control; Urban motorways; Variable speed limit**

## I. INTRODUCTION

Today, the road network in big cities is prone to everyday recurring congestion. To solve this problem many approaches are being applied, like intermodal transport, encouraging mode shift from car to public transport or non-motorized transport, building new transport infrastructure, etc. One approach is the application of solutions from the domain of Intelligent Transport Systems (ITS) i.e. establishing various services so that users can optimally use the transport network. One class of services from the ITS domain are related to road traffic control and are applied to urban and rural road networks to improve the Level of Service (LoS) and reduce accidents [1].

Urban motorways serve as bypasses around larger cities or to connect suburbs with the urban areas. As such, they can be analyzed as one special type of roads. They are designed to serve greater traffic demand providing high LoS. But, areas near on- and off-ramps become critical points at which congestion appears during peak hours. If the traffic demand at the on-ramp is higher and at the same time the mainstream flow is near its capacity value (metastable flow, see [2]), disturbance in the mainstream flow occurs. Consequently, a shock wave appears and propagates upstream. Since the traffic demand is changing during the day, dynamic speed limit service from the ITS domain known as Variable Speed Limit Control (VSLC) can be used to dynamically change the speed limit values according to the current traffic (in the focus of this paper) or weather situation. The aim of such a VSLC service is to alleviate the congestion effects [3].

On urban motorways, VSLC is applied upstream of the bottleneck location (location where the congestion occurs) to directly control the mainstream inflow rate into the congested area. Studies show that the application of VSLC can successfully alleviate traffic congestion and improve the LoS of an urban motorway regarding Travel Time (TT) [4], [5], decrease vehicle emissions [3], and increase traffic safety [4], [6].

Until now, many VSLC approaches are proposed in the literature. The aim of this paper is to compare three different controllers for VSLC. Two of them are reactive controllers. The first is called Mainline Virtual Metering (MVM) [5], and the second is called Simple Proportional Speed Control (SPSC) [7]. The third controller is based on Fuzzy Logic (FL) decision rules [8]. This comparison represents a continuation of the research started in [3]. For the sake of a more accurate comparison, the urban motorway stretch selected for simulation is modeled and calibrated using real traffic data. Calibration of the simulation model is done using real traffic data collected at a motorway of the State of California, USA [9]. Data were obtained from the Performance Measurement System (PeMS) database [10]. After the calibration of the simulation model, aforementioned VSLC controllers were adjusted to the congestion severity and traffic demand change rates. A simulation framework consisting of the microscopic traffic simulator VISSIM and MATLAB software was used to analyze VSLC controllers. The effects of the applied speed limit controllers are evaluated based on appropriately chosen Measures of Effectiveness (MoE).

This paper is organized as follows. Section 2 describes the implemented VSLC controllers. Creation of traffic scenarios is explained in section 3. Section 4 describes the simulation setup, and section 5 gives the obtained simulation results including discussion about the results. Paper ends with a conclusion and description of future work.

## II. CHOSEN CONTROLLERS FOR VSLC

VSLC systems are considered as a solution to solve traffic interference on urban motorways. For open-loop VSLC controllers, the traffic disturbances have to be completely known before its application. Considering the stochastic behavior of traffic demand, in most cases the prediction of traffic disturbances becomes challenging. Instead, closed-loop controllers have been widely used. They use the measured current traffic parameters to create a feedback-loop and compute the appropriate new speed limit trying to reduce the traffic congestion [11]. In continuation, the three controllers chosen for comparison are described.

*1) MVM:* This controller uses the flow-speed relationship to map desired flow value into speed limit values. It is based on the concept of ramp metering that increases the throughput of an urban motorway by limiting the on-ramp flow into the motorway mainstream flow. This mapping is done by a generalization of the ALINEA algorithm for ramp metering [4], [12] into a simple control law for VSLC. For this, the preceding motorway section is considered as an on-ramp for the next section. In this case, the ALINEA algorithm regulates the metered flow rate $Q_i$ from motorway section $i-1$ to section $i$ of the urban motorway as follows [5], [7]:

$$\bar{Q}_i(kT_1) = Q_i((k-1)T_1)+K_v[\rho_d-\frac{1}{N_{r,i}}\sum_{j\in I_{r,i}}\rho_j(kT_1)], \tag{1}$$

where $Q_i((k-1)T_1)$ present the flow from the previous time step, $\rho_d$ is the desired density [veh/km/lane], $I_{r,i}$ is the set of downstream sections relevant to section $i$, $N_{r,i}$ is the number of sections in the set $I_{r,i}$, $K_v = 4.5$ is the controller gain and remains the same for both MVM and SPSC controllers, and $\rho_j$ is the density of relevant downstream motorway sections in time step $k$ regarding section $i$. The controller generates its outputs every $T_1$ s, where $T_1 = N_C T_0$. $N_C$ is a positive integer (in this paper $N_C = 10$), and $T_0$ is the simulation sampling time (in this paper $T_0 = 30$ s).

New speed limit values have to be computed only if necessary which has to be detected. Let $C_i$ denote a control variable associated to each motorway section under VSLC control. To determine whether the control variable $C_i$ is active or not, density in the downstream section $\rho_{i+1}$ for the particular moment $kT_1$ has to be measured and tested [5], [7]:

S1 If $\rho_{i+1}(kT_1) \geq (1+\Delta_+)\rho_c$, where $\Delta_+$ is a positive design parameter, then $C_i$ is active;
S2 If $\rho_{i+1}(nk) \leq (1+\Delta_-)\rho_c$, where $\Delta_-$ is a negative design parameter, then $C_i$ is inactive;
S3 If neither of the two inequalities are not satisfied, $C_i$ maintains its status as in the previous control cycle.

The controller generates the desired speed limit $\overline{V}_i$ for the section $i$ using density data from the congested downstream section $i+1$. Flow commands computed using (1) have to be mapped into speed limit commands to control the traffic speed instead of the traffic flow. This is done by using the flow-speed relationship (2) as explained in [3].

$$\overline{V}_i(kT_i) = f(Q_i(kT_i)) \tag{2}$$

The speed limit $V_i(kT_i)$ in section $i$ has to be bounded due to traffic regulations as follows: $V_{min} = 60 \leq V_i(kT_i) \leq V_{max} = 130$ km/h.

*2) SPSC:* This controller responds to the changes in downstream density instead of maintaining a fixed desired density ($\rho_d$) [13]. It uses the same control variables for activation as MVM. The speed limit in each motorway section is again bounded with $V_{min}$ and $V_{max}$. In (3), the difference between density from the previous time step $k-1$ and current density of all affected downstream sections with respect to section $i$ is added to the speed limit value $V_i((k-1)T_1)$ from the previous time step [7]. Obtained result is the new speed limit value $\overline{V}_i(kT_1)$.

$$\begin{aligned}\overline{V}_i(kT_1) &= V_i((k-1)T_1) + \\ &K_v[\sum_{i=1}^{N-1}\rho_{i+1}((k-1)T_1) - \sum_{i=1}^{N-1}\rho_{i+1}(kT_1)]\end{aligned} \tag{3}$$

For both controllers, final speed limit value is checked before it is send on the VMS to ensure smooth speed limit change. The final speed limit $V_i$ is then obtained as:

$$V_i(kT_1) = \begin{cases} V_i((k-1)T_1) - C_v, & \text{if } \overline{V}_i(kT_1) \leq V_i((k-1)T_1) - C_v \\ V_i(kT_1) + C_v, & \text{if } \overline{V}_i(kT_1) \geq V_i(kT_1) + C_v \\ \overline{V}_i(kT_1), & \text{otherwise} \end{cases}, \tag{4}$$

where $C_v$ is a positive constant which represents the maximal allowed change of the speed limit between two consecutive control time steps (usually 10 km/h, used also in this paper) and $V_i(kT_1)$ is the final speed limit for section $i$ [13].

*3) FL:* This controller uses fuzzy logic rules to decide about the appropriate speed limit value. The difference between the two previously mentioned controllers and this one is that in the described controllers the speed limits are determined based on pre-specified threshold values for flow, density, and average speed, while the FL controller can set the speed limit according to a combination of fuzzy rules [8]. The membership functions have to be adjusted according to the situation, which means that the membership functions differ for different analyzed periods [9]. Therefore, the rules used for the implementation of this controller are listed below. It is good to mention that the rules have different weights because one of the rules can imply the result more than another one.

1. If (Flow is low) then (Speed Limit is high) - Weight: 1;
2. If (Flow is medium) then (Speed Limit is medium) - Weight: 1;
3. If (Flow is high) then (Speed Limit is low) - Weight: 2;
4. If (Density is high) then (Speed Limit is low) - Weight: 2.

## III. TRAFFIC SCENARIOS

### A. Motorway section

Comparison of chosen VSLC approaches is done by using a stretch of the motorway Interstate 80 located in the State of California, USA. It is part of the District 4 (Bay Area) [9]. The chosen segment has 5 lanes, length of 7 km, 12 vehicle detectors, and originally 2 VMS and 4 on-ramps. Three on-ramps are equipped with ramp metering. The stretch is shown in Fig. 1. Each detector is located in a certain milepost according to the PeMS database providing traffic data. For comparison of the mentioned algorithms, the VMS signs are placed at the beginning of section $L_1$, $L_5$ and $L_7$. The shaded green regions represent areas under VSLC but only the middle one was active in this analysis. One has to note that vehicles decelerate before the VMS in a real-world situation, but in the applied simulator, vehicles do not react until they pass the VMS. This phenomenon is indicated by a shift of the green region into the respective downstream section.

### *B. Traffic data*

The PeMS database provides flow, speed, and density data across the detectors in the form of time series data collected during the day. The road segment presented in Fig. 1 was modeled in the microscopic simulator VISSIM. For this, it was necessary to select a period for an analysis. The traffic data considered the period from 00:00 to 23:59 on the first of August, 2016. The first traffic scenario is modeled according to traffic data from the morning period, while the second one described traffic during the noon period.

The morning period is from 8:00 to 11:00. The average flow is approximately 6000 veh/h. During the entire period, traffic flow has a small variation across the entire motorway stretch that can be characterized as metastable traffic flow [2]. This is an appropriate scenario for testing of the abilities of the mentioned controllers.

The noon period is composed of two hours from 12:00 to 14:00. This period is characterized by constant higher traffic flow than 7000 veh/h. The first peak is roughly 8000 veh/h at 12:30, while another one is achieved at 13:20 with the load of 7700 veh/h. During the noon period, higher demand is present most of the time and the VSLC controllers are able to make smaller improvements compared to the morning period. Therefore, this scenario is used to show how the VSLC controllers react in critical traffic situations [9].

## IV. SIMULATION SETUP

In this section, the simulation framework used for controller analysis is defined, and the calibration of the modeled network is discussed.

### *A. Model calibration*

A comparison between the data obtained from the VISSIM simulation data and the real traffic data obtained from PeMS was done to check if the simulation model can accurately represent the real traffic situation. This comparison was done by using the GEH statistic given with (5):

$$GEH = \sqrt{\frac{2(M-C)^2}{M+C}}, \tag{5}$$

where $M$ represents hourly traffic volume from the simulated traffic model and $C$ is the real hourly traffic data obtained from PeMS database. To achieve a good calibration, the GEH value should be less than $5$ for more than $85\%$ of the individual links.

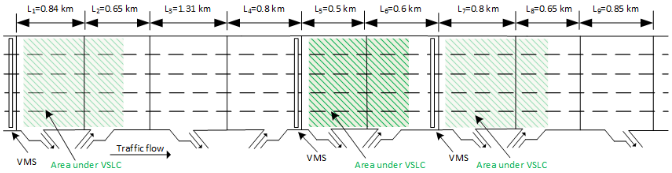

Figure 1. Modeled motorway stretch consisting of 9 segments

The GEH values between ($5$ and $10$) indicate some deviations between real traffic data and data obtained from the simulation. The obtained result for the morning period is $5.6$ on average and for the noon period, GEH is $4.3$. For the morning period, an additional check was done and there were no significant deviations. Therefore, the simulation models can be accepted.

### *B. Simulation parameters*

Simulation framework contains VISSIM microscopic simulator and programming platform MATLAB [3]. Realistic driver behaviors for motorway stretch including the area around on- and off-ramps are tuned based on [14] where a calibrating process for VISSIM used to simulate the traffic flow on German motorways is explained. Acceleration rate is set to $1.5$ m/s$^2$, while headway is set to be 3 s. The other parameters used in this analysis can be found in [9]. The simulated traffic flow is composed of $98\%$ passenger cars and $2\%$ of heavy vehicles.

## V. OBTAINED RESULTS

Chosen MoEs for the comparative analysis are TT and Total Time Spend (TTS). TT is a simple measure that measures the time one vehicle needs to travel through an observed motorway stretch and is related to mainstream traffic only. TTS represents the amount of time spent by all of the vehicles on the motorway including on- and off-ramps.

### *A. Morning period*

The quantitative analysis regarding the TT, TTS, delay and queue length obtained during this period is shown in Table I. Regarding the traffic parameters, two of the controllers reacted correctly (MVM and FL) reducing the average values compared to the non-control case. The MVM and FL controllers resulted in improvements in all of the measured MoE, except in values for average delay, which was increased for the MVM case. The SPSC controller did not show significant improvements and had only a minor impact on improvements in the queue length. It is also possible to state that the reason for poor results of SPSC is the fact that its output speed limit can oscillate, causing unstable traffic conditions.

### *B. Noon period*

The results obtained for this period can be seen in Table II. Despite the problem with congestion during the noon period, the controllers have been able to reduce almost all of the compared parameters in this case. Reduction of TTS has been achieved for all controllers where SPSC reduction is $0.6\%$, the MVM $4\%$ and in case of FL, the improvement is $3.9\%$. The fact that the improvements are not significant, proves that the controllers, when are applied to a congested period, have a limited impact [9].

### *C. Discussion*

The working principle of the compared VSLC controllers is essentially based on the timely detection of congestion (increased density) in the traffic flow and taking a preventive action by changing the speed limit. All aimed towards keeping

TABLE I. QUANTITATIVE ANALYSIS FOR THE MORNING PERIOD

| | No VSLC | SPSC | | MVM | | FL | |
|---|---|---|---|---|---|---|---|
| | | **Obtained** | **Reduction** [%] | **Obtained** | **Reduction** [%] | **Obtained** | **Reduction** [%] |
| $TTS$ [veh·h] | 16415.1 | 16367.8 | 0.3 | 14396.0 | 12.3 | 15760.8 | 4.0 |
| Average $TT$ [s] | 419.7 | 425.5 | −1.4 | 403.3 | 3.9 | 357.7 | 14.8 |
| Maximal $TT$ [s] | 2908.5 | 3312.0 | −13.9 | 1654.4 | 43.1 | 1680.1 | 42.2 |
| Average delay [s] | 146.7 | 163.5 | −11.4 | 189.5 | −29.2 | 108.2 | 26.3 |
| Maximum delay [s] | 2615.3 | 3005.7 | −14.9 | 1371.4 | 47.6 | 1483.7 | 43.3 |
| Average queue length [veh] | 1.6 | 0.4 | 76.8 | 0.2 | 87.4 | 1.2 | 21.6 |
| Maximal queue length [veh] | 5.0 | 4.0 | 20.0 | 3.0 | 40.0 | 4.0 | 20.0 |

TABLE II. QUANTITATIVE ANALYSIS FOR THE NOON PERIOD

| | No VSLC | SPSC | | MVM | | FL | |
|---|---|---|---|---|---|---|---|
| | | **Obtained** | **Reduction** [%] | **Obtained** | **Reduction** [%] | **Obtained** | **Reduction** [%] |
| $TTS$ [veh·h] | 11439.0 | 11372.5 | 0.6 | 10986.6 | 4.0 | 10996.1 | 3.9 |
| Average $TT$ [s] | 622.6 | 621.7 | 0.1 | 617.3 | 0.9 | 598.5 | 3.9 |
| Maximal $TT$ [s] | 1563.3 | 1534.9 | 1.8 | 1489.0 | 4.8 | 1889.7 | −20.9 |
| Average delay [s] | 502.9 | 504.3 | −0.3 | 474.0 | 5.7 | 489.3 | 2.7 |
| Maximum delay [s] | 1512.0 | 1503.6 | 0.6 | 1489.0 | 1.5 | 1356.0 | 11.0 |
| Average queue length [veh] | 2.3 | 2.3 | 0 | 2.1 | 10.9 | 1.25 | 45.7 |
| Maximal queue length [veh] | 20 | 23 | −15 | 23 | −15 | 20 | 0 |

the traffic parameters within acceptable values. By applying VSLC, the MoEs were maintained within acceptable limits during the morning and noon period. In the case without VSLC, most MoE measures in the motorway stretch slightly exceed the values obtained by applying VSLC. There was also a significant reduction of the queue length at on-ramps when VSLC was applied.

## VI. CONCLUSION AND FUTURE WORK

Three reactive VSLC controllers MVM, SPSC, and FL have been applied in a microscopic simulation environment. Comparative analysis is conducted on a motorway stretch that was calibrated using real traffic data obtained from the PeMS database. Results show that VSLC controllers improve the traffic-related MoEs compared to the no-control case.

Future work on this topic will include an augmentation of the simulation framework that will enable simulation of different compliance rates of drivers to the imposed speed limit. Additionally, optimization of rules for the FL controller by applying an optimization method based on the genetic algorithm will be developed and evaluated.

## ACKNOWLEDGMENT

The authors thank the company PTV Group and the Faculty of Transport and Traffic Sciences, University of Zagreb for supporting the work published in this paper. Gabriel Oliveira Melo was supported by a training grant in the scope of the Brazilian AUSPIN entrepreneurship program. This work has been partly supported by the University of Zagreb under the short term support „Application of deep learning in intelligent traffic control“ and by the European Regional Development Fund under the grant KK.01.1.1.01.0009 (DATACROSS). This research has also been carried out within the activities of the Centre of Research Excellence for Data Science and Cooperative Systems supported by the Ministry of Science and Education of the Republic of Croatia.

## REFERENCES

[1] O. Pribyl, M. Koukol, and J. Kuklova, "Computational Intelligence in Highway Management: A Review," *PROMET - Traffic&Transportation*, vol. 27, Oct. 2015.

[2] B. S. Kerner and H. Rehborn, "Experimental features and characteristics of traffic jams," *Physical Review E*, vol. 53, pp. R1297–R1300, Feb. 1996.

[3] K. Kušić, N. Korent, M. Gregurić, and E. Ivanjko, "Comparison of two controllers for variable speed limit control," in *2016 International Symposium ELMAR*, (Zadar, Croatia), pp. 101–106, 12-14 Sept 2016.

[4] M. Papageorgiou, E. Kosmatopoulos, and I. Papamichail, "Effects of variable speed limits on motorway traffic flow," *Transportation Research Record: Journal of the Transportation Research Board*, vol. 2047, pp. 37–48, 2008.

[5] M. Hadjipollas, M. Lestas, O. Ioannou, G. Hadjipollas, and A. Pitsillides, "Evaluation of new ramp metering and variable speed limit algorithms on the Cyprus Highway Network," *International Trade and Freight Transportation Conference (ITFTC2008)*, pp. 171–177, 2008.

[6] P. Rama and A. Schirokoff, "Effects of weather-controlled variable speed limits on injury accidents," in *18th International Cooperation on Theories and Concepts in Traffic Safety*, (Helsinki, Finland), 2005.

[7] W. Yun, *Dynamic Variable Speed Limit Control: Design, Analysis and Benefits*. PhD thesis, University of Southern California, USA, 2011.

[8] D. Li and P. Ranjitkar, "A fuzzy logic-based variable speed limit controller: Fuzzy logic variable speed limits," *Journal of Advanced Transportation*, vol. 49, pp. 913–927, Dec 2015.

[9] G. O. Melo, M. Gregurić, and E. Ivanjko, "Variable speed limit control on urban highways," Final Report FPZ-ZITS-01-2017, University of Zagreb, Faculty of Transport and Traffic Sciences, Croatia, July 2017.

[10] Caltrans, "PeMS Data Source - State of California, PeMS database." http://pems.dot.ca.gov/. [accessed 06 April 2017].

[11] A. Hegyi, B. De Schutter, and H. Hellendoorn, "Model predictive control for optimal coordination of ramp metering and variable speed limits," *Transportation Research Part C: Emerging Technologies*, vol. 13, pp. 185–209, June 2005.

[12] M. Papageorgiou, H. Hadj-Salem, and J.-M. Blosseville, "ALINEA: A local feedback control law for on-ramp metering," *Transportation Research Record*, no. 1320, 1991.

[13] R. C. Carlson, I. Papamichail, and M. Papageorgiou, "Mainstream Traffic Flow Control on Freeways Using Variable Speed Limits," *TRANSPORTES*, vol. 21, p. 56, Nov. 2013.

[14] U. Leyn and P. Vortisch, "Calibrating VISSIM for the German Highway Capacity Manual," *Transportation Research Record: Journal of the Transportation Research Board*, vol. 2483, pp. 74–79, Oct. 2015.