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INFLUENCE OF SPATIAL PLACEMENT OF VARIABLE SPEED LIMIT ZONES ON URBAN MOTORWAY TRAFFIC CONTROL

ABSTRACT

Traffic control approaches, in particular Variable Speed Limit (VSL), are often studied as solutions to improve the level of service on urban motorways. However, the efficiency of VSL strongly depends on the spatiotemporal arrangement of VSL zones. It is crucial to determine the lengths and locations of VSL zones for best VSL efficiency before deployment in a real system, as the optimal length of the VSL zone and its distance from the bottleneck directly affects traffic dynamics and, thus, bottleneck control. Therefore, in this study, we perform the analysis of different VSL zones lengths and their positions by using a closed-loop Simple Proportional Speed Controller for VSL (SPSC-VSL). We evaluate the different VSL zone configurations and their impact on traffic flow control and vehicle emissions in a SUMO microscopic simulation on a high traffic demand scenario. The results support the observations of previous researchers on the significant dependence of VSL zone placement on VSL efficiency. Additionally, new data-based (traffic parameters and vehicle emissions) evidence of the performance of the SPSC-VSL design are provided regarding the best placement of consecutive VSL zones for motorway bottleneck control not analysed in previous research.

KEYWORDS

intelligent transportation systems; traffic control; variable speed limit; urban motorways; speed limit and acceleration zones.

1. INTRODUCTION

Urban motorways are used to serve transit and local traffic with the main purpose to serve local traffic. They are characterised with many closely placed on-ramps and off-ramps. The ever-increasing traffic demand for urban motorway capacity often leads to recurring congestions and capacity drops. Main points of interest where congestion often occurs are near on-ramps due to local traffic flow merging into the mainstream motorway flow. Resulting congestions frequently occur during morning and afternoon peak hours. The speed deviations between mainstream flow and on-ramp flow are more pronounced when the on-ramp flow merges into the mainstream flow which disrupts the mainstream flow, and a bottleneck starts forming. Such speed deviations often form shockwaves that propagate upstream regarding the mainstream traffic flow [1]. Thus, mainstream flow becomes unstable and less safe [2]. The Level of Service (LoS) of the urban motorway is then reduced which in term decreases the effective motorway capacity as well as the average speed, and increases traffic density and Travel Time (TT). LoS is a measure used to describe the traffic state labelled with letters from A to F using density and speed measurements, according to the Highway Capacity Manual [3]. When the effective motorway capacity reduces, traffic flow measured immediately after the bottleneck area is significantly reduced in relation to the maximum possible capacity of the observed segment [1, 4].

Traffic control is one of the services from the domain of Intelligent Transportation Systems (ITS) that can alleviate congestion. Variable Speed Limit (VSL) is a traffic control approach derived from the ITS domain that uses Variable Message Signs (VMS) to apply appropriate speed limits on urban motorways based on the current meteorological and/or traffic state. VSL can be integrated and operated synchronously with other ITS services such as Ramp Metering to provide more efficient traffic control if VSL is unable to maintain the desired flow capacity within the congested motorway section [5]. In general, VSL is used to harmonise the speeds of congested downstream traffic and upstream free-flow traffic and to mitigate the occurrence of congestion and shockwaves, as described in [6]. VSL indirectly controls the inflow of vehicles into the problematic motorway segment [7]. Thus, the VSL control system aims to keep traffic volumes close to the available operating capacity of the motorway section for current traffic conditions without the need for additional lanes. This can reduce or prevent the likelihood of traffic breakdown. The effect of VSL zone length and acceleration zone length (the distance between VSL zone and bottleneck location) is analysed in [6]. Results obtained in [6] define the main motivation for this research to extend the work in [6] to two VSL applicable zones and to analyse various VSL and acceleration zones lengths. Thus, the use of two consecutive VSL zones is analysed to examine the effect of improved speed harmonisation and to mitigate the congestion intensity better.

In our previous work [8], we implemented and tested the Simple Proportional Speed Limit Controller for VSL control (SPSC-VSL) originally proposed in [9]. It should be noted that in the modelling described in [9] and [8] the authors did not elaborate the effect of different VSL configurations on SPSC-VSL performance. Analysis in [6] shows the existence of strong correlation between different VSL zones configurations (speed limit zone length and its distance from the bottleneck location) and VSL efficiency. Thus, this primarily drives our research in which we assess the contribution of different VSL zones configurations particularly to SPSC-VSL efficiency. For this, we perform an analysis regarding the different VSL zones lengths and acceleration areas and their impact on traffic flow optimisation using the SPSC-VSL controller. To be consistent, we performed experiments with different VSL application and acceleration area (zone) lengths conducted on a traffic scenario with a high traffic demand and pronounced congestion in the mainstream traffic flow using the microscopic simulator SUMO [10]. Activation threshold and controller gain parameters were also analysed. The results of SPSC-VSL were compared with the no control scenario (No VSL).

This paper is organised as follows. The second section explains the effect of VSL regarding motorway traffic control. The following third section describes the applied SPSC-VSL. Fourth section gives insight into the applied methodology. The fifth section describes the implemented simulation framework followed by the sixth section containing obtained results including a discussion. The paper ends with a conclusion and future work section.

2. MOTORWAY TRAFFIC CONTROL USING VSL

As mentioned, VSL is a control strategy from the domain of ITS services used for congestion alleviation and, generally, increasing the LoS on the motorway. VSL control systems alert drivers about the current speed limit using VMS, whose efficiency is dependent of their positioning [6]. The speed limits are set based on real-time data of the current state of traffic and/or weather or environmental conditions.

Two main strategies used in VSL systems are speed harmonisation and traffic breakdown prevention [2]. The contribution of speed harmonisation lies in reducing the speed variance between vehicles within the lane and between the lanes. The average speed of vehicles is lowered below the values that enable the appearance of critical traffic density, thus, stabilising the flow and making it safer [1, 2]. Traffic breakdown prevention focuses on reducing the flow using appropriate speed limits, to lower the inflow into high traffic density areas and to increase throughput [1, 2].

2.1 Influence on the fundamental diagram

The application of VSL modifies the fundamental diagram (traffic flow q and traffic density ρ dependence diagram) of the controlled motorway section [7]. Slope differences between the cases of No VSL and applied VSL are visible in *Figure 1*. When the traffic flow is stable, the density ρ (veh/km) is less than the critical density ρ_c (left green side in the fundamental diagram, *Figure 1*) and traffic is smooth with low interaction rates between vehicles [11]. Applying speed limits under critical densities decreases the slope of the fundamental flow-density diagram, thus, leading to reduced traffic flow (q_{VSL_i}) from the VSL area. Furthermore, lower speed limits cause larger slope decreases [12]. The aforementioned effect can be used to reduce the traffic inflow rate into the downstream bottlenecks if VSL is applied on a sufficiently long area located far enough upstream of the bottleneck.

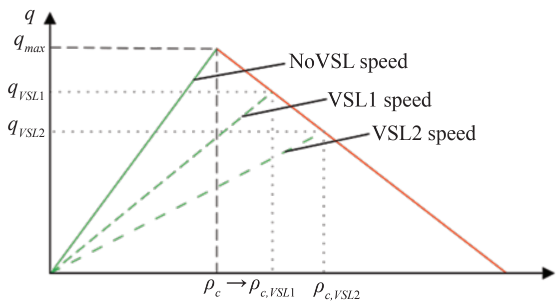


Figure 1 – Triangular fundamental diagram with and without applied VSL

At density values above the critical density ($\rho > \rho_c$) the traffic flow becomes unstable (right red side in the fundamental diagram, *Figure 1*) and vehicles interactions are more prominent. This may lead to shockwaves causing a chain reaction, resulting in a complete traffic jam on the motorway [11]. VSL moves the critical density to higher values in the flow-density diagram [12], thus, enabling more vehicles to be placed within the controlled motorway section without falling into unstable traffic state. This means that the average speed at densities larger than the ρ_c will be higher when a speed limit is set, attributing to the effect of speed harmonisation mentioned earlier.

2.2 Influence of speed limit and acceleration zones placement

According to [6], a longer VSL zone results in longer delays and a slower system. Length of the acceleration area also affects the system's functionality. Since vehicles leaving the VSL zone must travel a longer distance to reach the bottleneck, longer acceleration areas might cause higher delays. Though, because vehicles mostly travel faster in the acceleration area than in the VSL zone, the aforementioned effect should be less prominent than the delay induced by the longer VSL zone. Aside from that, acceleration area length also impacts the speed at which vehicles reach the bottleneck. An example given in [6] shows that a too short acceleration area could be insufficient for vehicles to reach the critical speed at the bottleneck, thus adding the possibility of compromising the merging behaviour of vehicles and causing the system to operate suboptimally. The best result in terms of Total Time Spent (TTS) was achieved with an acceleration area length of about 175 m, since longer areas caused an increase in delay, while shorter areas were not long enough for vehicles to accelerate to the critical speed. In terms of the VSL zone length, a shorter VSL zone (the best results were observed with the VSL zone length of 100 m) led to better results, but the authors emphasised that when applied in the field, multiple conflicting speed limit signs close to each other could confuse drivers.

3. SIMPLE PROPORTIONAL SPEED LIMIT CONTROLLER

One of the desirable characteristics of VSL controllers is their stable behaviour under fluctuating traffic conditions. At the same time, it is desirable to have a less complex controller so that it can be implemented and tested in a simulation framework and easily adjusted for real-world deployments. Therefore, the SPSC-VSL was proposed in [9]. SPSC-VSL is a simple feedback based VSL controller that can respond appropriately to changes in downstream density on controlled motorway sections.

To release a disturbance in the downstream motorway section N+1 (section L3 where bottleneck occurs, see *Figure 3*), the N controlled sections that are upstream of the section N+1 would be active and respond to their downstream density changes using *Equation 1*. Therefore, SPSC-VSL attempts to adjust the speed limit of the upstream flow to reduce the inflow to the downstream motorway region to minimise the differences between the densities measured from the previous control time step t and the currently measured density on the controlled motorway segment. In *Equation 1*, the difference of the sum of measured densities of all affected downstream sections from the previous control time step $\rho_j(t\text{-}1)$ and the sum of current densities $\rho_j(t)$ with respect to section i is added to the speed limit value from the previous control time step $V_i(t\text{-}1)$. Impact of density changes on the new speed limit $\overline{V}_i(t)$ can be set by the positive proportional gain K_v:

$$\bar{V}_i(t) = V_i(t-1) + K_v\left[\sum_{j=i+1}^{N+1} \rho_j(t-1) - \sum_{j=i+1}^{N+1} \rho_j(t)\right] \tag{1}$$

To achieve smooth speed transition and to prevent big oscillations between two consecutive speed limits, the new speed limit in section i is bounded using *Equation 2*. Parameter C_v represents maximal allowed speed change between two consecutive control time steps and it is set to 20 km/h.

$$V_i(t)=\begin{cases} V_i(t-1)-C_v, & if \quad \bar{V}_i(t)\leq V_i(t)-C_v \\ V_i(t-1)+C_v, & if \quad \bar{V}_i(t)\geq V_i(t)+C_v \\ \bar{V}_i(t), & otherwise \end{cases} \tag{2}$$

The downside of the SPSC-VSL controller is evident in the frequent changing of speed limits due to the nature of *Equation 1*. To further stabilise the SPSC-VSL, an additional variable C_i (veh/km/lane) is introduced to control the activation of the controller. If the density in the adjacent section (i+1) at control time step t is greater than the predefined activation threshold C_i , a new speed limit calculation is required in section i. Both the activation variable and the controller gain values were selected from multiple tests.

Nevertheless, SPSC-VSL does not undergo modelling (e.g. the flow-speed fundamental model is not required which might be challenging to estimate for a real system). SPSC-VSL is highly scalable; there is no limit on the number of motorway sections to be controlled. Consequently, multiple adjacent VSL zones upstream from the congested area can achieve smooth speed transition between the downstream congested flow and the free-flow arriving at the bottleneck. However, to further optimise SPSC-VSL, an analysis of appropriate VSL zones lengths and their positions is mandatory. Therefore, in the next section, an analysis methodology for efficient spatial placement of VSL zones regarding their lengths and starting points from the bottleneck is introduced.

4. ANALYSIS METHODOLOGY

As mentioned, in this section, we describe the methodology used in our experiment in detail regarding the impact of different VSL and acceleration zone lengths on VSL efficiency. We conducted our experiment using the SPSC-VSL controller [8, 9]. The main hypothesis about influence of different VSL zones and their acceleration part was analysed in [6]. The results have shown a strong correlation of spatial location of VSL zones and their distance from the bottleneck locations regarding traffic flow optimisation. To be more precise, the VSL zone is referred to as an area where the speed limit is controlled by a VSL controller. In our experiment, we use two VSL zones (L1 and L2) controlled by the SPSC-VSL controller (*Figure 3*). To ensure optimal bottleneck operation vehicles must enter the bottleneck with the so-called critical speed [6]. Due to the frequently oscillating location of the creation of the bottleneck in the mainstream flow within the merging area of the on-ramp r_3 in our simulation model (*Figure 3*), it is hard to determine the exact location of the bottleneck activation. What was observed during the simulations is that when a little activation of the bottleneck is created, it is likely that at the very beginning, the formed disturbance (congestion) will propagate upstream at least 50-100 m. As a result, the ending point of the acceleration area is set at the position of 5.3 km (starting position of the on-ramp r_3) so that vehicles are still able to accelerate after leaving the VSL zone and enter the bottleneck tail with the critical speed as the results from [6] suggested.

Thus, in our experiment we choose three VSL zone configurations 100-100, 300-300, 500-500 m (first value is referred to as L_1, while the second for L_2 zone length as denoted in *Figure 3*), and three acceleration areas 100, 200, 300 m, respectively. Both VSL zones are adjacent to each other and are spatially adjusted so that VSL2 zone is always adjacent to its downstream defined acceleration area. As a result, 9 different VSL configurations are used in our simulation experiment. We will refer to them in the sections below as follows. For example, VSL configuration with two VSL application zones both of length 300 m and 100 m of the acceleration area is abbreviated as 300-300-100. The same principle is applied for other configurations.

5. SIMULATION FRAMEWORK

In our simulation experiment, different VSL zones configurations were compared to analyse their effect on the SPSC-VSL control optimisation. The applied simulation framework consists of microscopic simulator SUMO and programming platform MATLAB (*Figure 2*).

5.1 Motorway model and traffic data

The motorway model used for testing specific scenarios is based on the model used in [13]. The total length of the motorway model is 8 km. It contains two on-ramps (r_1 and r_3) and one off-ramp r_2. The total length of each ramp is 0.5 km. The model contains three main sections used for SPSC-VSL control VSL zones (L_1 and L_2) and congestion section L_3.

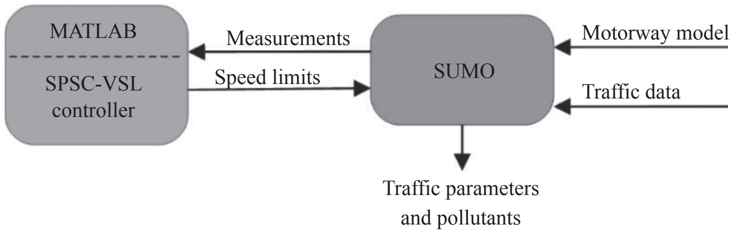


Figure 2 – Simulation framework

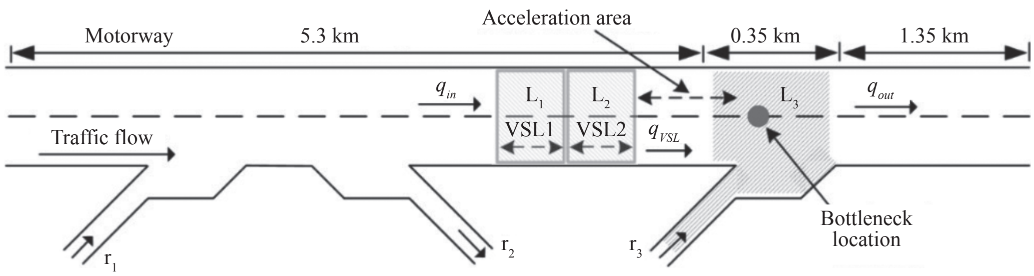


Figure 3 – Motorway model

In L_3, the bottleneck is created between the on-ramp r_3 and the lane drop (see *Figure 3*). VSL zones are equipped with VMS on which the new speed limits are displayed depending on the current traffic conditions. The congestion is created by the additional traffic demand created on the mainstream and at the on-ramp r_3 causing bottleneck activation in the merge area. The traffic flow demand used in our simulation experiment has been defined according to *Figure 4*. The additional peak flow created on the mainstream (between 42-47 simulation minutes) and the highest demand at on-ramp r_3 creates the pronounced congestion in the merge area (section L_3). It is important to note that the calibration procedure of the simulated segment of the motorway is not included because a synthetic model with corresponding traffic flow was used in this analysis. This research aims to establish a methodology to evaluate the impacts on traffic flow and vehicle emissions regarding the different VSL zone configurations and their impact on SPSC-VSL performance. To test the VSL zones lengths impact on a particular motorway section, appropriate traffic data gathering, and simulation model calibration has to be done. After this being done, the methodology defined in this paper can be applied in the same way as described here for any particular motorway section.

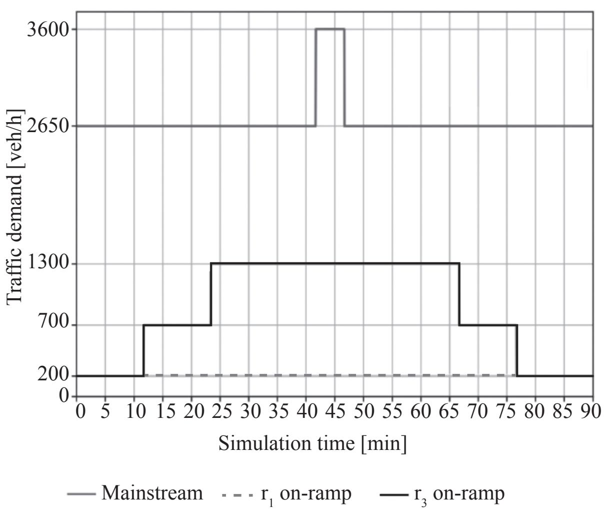


Figure 4 – Traffic demand

5.2 Spatiotemporal traffic parameters

To evaluate the efficiency of the SPSC-VSL and to depict spatiotemporal distribution of speed and density across the observed motorway segment, the simulated motorway model is initially divided into smaller sections each with the length of 50 m. By doing so, the microscopic simulator SUMO enables the detailed traffic state presentation of the simulated motorway network at any particular time step, thus enabling spatiotemporal analysis of traffic flow behaviour during simulation. Mainstream traffic parameters such as average vehicle speed and traffic flow density were measured every 10 s. In addition, to get a better insight of the influence of SPSC-VSL and different VSL zones configurations on traffic flow, additional environmental parameters, such as carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NO_x) and Particular Matters (PM_x)

were measured. Finally, overall TTS is measured on the entire motorway model including mainstream and all ramps. This measure was chosen because the travel time on motorway mainstream and ramp waiting times are included in just one measure representing the traffic state on the whole motorway network.

5.3 Simulation parameters

Tested simulation scenario lasts for 1.5 h. Nominal speed limit value in free-flow conditions is set to 120 km/h, while in congested traffic regime speed limit can be reduced up to 60 km/h with a maximal step size of 20 km/h. A new speed limit value is sent to the VMS every 2.5 min. The controller parameters K_v and C_i were both selected from several tests for each VSL zones configurations (keeping a fixed acceleration length of 100 m) considering the TTS minimisation criteria. Therefore, for the VSL zones with the application areas 100-100 m and 300-300 m, values K_v=4.5 and C_i=23 veh/km/lane, while for the VSL zones lengths of 500-500 m, values K_v=4.5 and C_i=26 veh/km/lane were used. In the tested scenario, mainstream flow consists of 94% of passenger cars, 3% of trucks and 3% of buses. As already mentioned, the input traffic data used were synthetic, and the calibration process of the simulated model is not included in this paper. Therefore, the driving dynamics of vehicles were modelled using the Krauss car-following model with default parameters as set in the used microscopic simulator SUMO [10]. It is important to note that the purpose of this study is not to assess the extent to which SPSC-VSL can improve traffic, but to investigate how different configurations of VSL zones affect SPSC-VSL. Thus, the improvement with respect to the No VSL scenario should mainly be considered as a measure of comparison between two different control scenario settings rather than an absolute measure of performance.

6. SIMULATION RESULTS

In this section, we analyse the influence of the lengths of the VSL zones and their distances to the bottleneck (acceleration area) on the optimisation of the traffic flow. The experiments performed were evaluated with the corresponding Measures of Effectiveness (MoEs). Average vehicle speed and average traffic density were measured within the bottleneck area (section L_3). Environmental parameters measured during the simulation are CO, CO_2, NO_x and PM_x. They enrich information about the traffic situation together with the macroscopic traffic parameters (density and average speed) since the sudden braking and acceleration of vehicles within congested traffic causes additional fuel consumption and thus, higher pollution. The baseline No VSL case is used to evaluate the obtained results.

6.1 Influence of VSL and acceleration area lenghts on traffic parameters

In *Figure 5*, the TTS measured on the entire motorway network for simulated cases is shown. There are 3 cases with lower TTS than the No VSL case. The best result is achieved for VSL configuration 300-300-100 in which each VSL zone has the length of 300 m, and the acceleration area is equal to 100 m. The achieved improvement is 1.38% compared with No VSL case. Similar result is achieved in case of VSL configuration 500-500-100. Therefore, a shorter acceleration zone decreases the delay and leads to better congestion resolving.

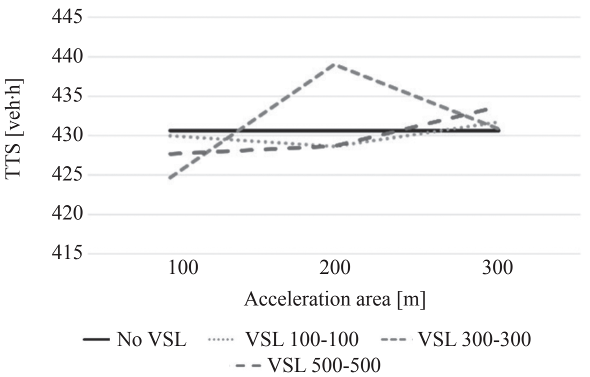


Figure 5 – Variation of TTS with the lengths of VSL zones and acceleration zones

Figure 6 shows the change in average speed in the bottleneck area as a function of the lengths of the VSL zones and the acceleration areas. The VSL zone configuration 500-500 m with acceleration area of 100 m gives the best result (notation 500-500-100). Also, the VSL zone configuration 300-300 m with the acceleration length of 300 m (notation 300-300-300) achieved good performance regarding the measured average speed within the bottleneck area. For all acceleration areas in the case of VSL zones lengths 100-100 m, the measured speed is in line with the No VSL case or slightly below it.

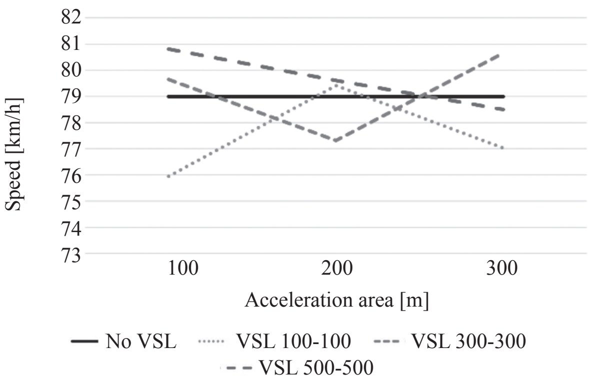


Figure 6 – Variation of average speed in L_3 with the lengths of VSL zones and acceleration zones

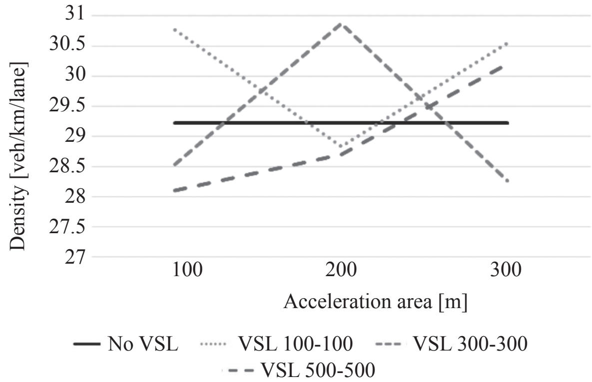


Figure 7 – Variation of average density in L_3 with the lengths of VSL zones and acceleration zones

In *Figure 7*, the average density in relation to different VSL configurations is shown. The highest density 30.87 veh/km/lane is achieved for scenario 300-300-200, representing the worsening of -5.65% compared with density of 29.22 veh/km/lane in No VSL case. The best case is obtained for configuration 500-500-100 with the density value of 28.10 veh/km/lane. Compared with the No VSL case the average density in L_3 is reduced by 3.83%. Regarding traffic density reductions, the VSL configuration 300-300 is giving favourable results too, where the acceleration zones lengths of 100 and 300 m were used. The most significant reduction in vehicle emissions is achieved with the 500-500-100 VSL configuration. The positive impact of the controllers on CO_2 emissions is up to 1.25%, on CO emissions up to 2.97%, on NO_x emissions up to 1.14% and on PM_x emissions up to 1.16% per simulated traffic scenario. A complete list of results for all analysed cases can be found in *Tables 1, 2, and 3*.

Table 1 – Obtained MoEs in case of VSL zones lengths 100-100, and different acceleration zones lengths

VSL zones lengths [m]	No VSL	100-100					
Acceleration zone length [m]		100		200		300	
		Obtained	Improv. [%]	Obtained	Improv. [%]	Obtained	Improv. [%]
TTS [veh·h]	430.63	429.99	0.15	428.65	0.46	431.74	-0.26
Avg. speed in L_3 [km/h]	79	75.95	-3.86	79.41	0.52	77.03	-2.49
Avg. density in L_3 [veh/km/lane]	29.22	30.77	-5.3	28.33	1.33	30.55	-4.55
CO_2 [kg]	9,473.84	9,465.31	0.09	9,427.56	0.49	9,530.76	-0.60
CO [kg]	120.31	119.99	0.27	119.63	0.57	120.61	-0.25
NO_x [kg]	20	20	0	19.8	1	20.13	-0.65
PM_x [kg]	452.33	452.07	0.06	449.2	0.69	454.4	-0.46

Table 2 – Obtained MoEs in case of VSL zones lengths 300-300, and different acceleration zones lengths

VSL zones lengths [m]	No VSL	300-300					
Acceleration zone length [m]		100		200		300	
		Obtained	Improv. [%]	Obtained	Improv. [%]	Obtained	Improv. [%]
TTS [veh·h]	430.63	424.69	1.38	439.04	-1.95	430.85	-0.05
Avg. speed in L_3 [km/h]	79	79.64	0.81	77.31	-2.14	80.65	2.09
Avg. density in L_3 [veh/km/lane]	29.22	28.54	2.33	30.87	-5.65	28.26	3.29
CO_2 [kg]	9,473.84	9,398.6	0.79	9,480.61	-0.07	9,429.61	0.47
CO [kg]	120.31	117.75	2.13	119.72	0.49	119.23	0.89
NO_x [kg]	20	19.8	1	20.18	-0.88	19.84	0.79
PM_x [kg]	452.33	447.1	1.16	454.79	-0.54	449.73	0.57

Table 3 – Obtained MoEs in case of VSL zones lengths 500-500, and different acceleration zones lengths

VSL zones lengths [m]	No VSL	500-500					
Acceleration zone length [m]		100		200		300	
		Obtained	Improv. [%]	Obtained	Improv. [%]	Obtained	Improv. [%]
TTS [veh·h]	430.63	427.7	0.68	428.7	0.45	433.7	-0.71
Avg. speed in L_3 [km/h]	79	80.8	2.28	79.6	0.76	78.5	-0.63
Avg. density in L_3 [veh/km/lane]	29.22	28.1	3.83	28.7	1.78	30.2	-3.35
CO_2 [kg]	9,473.84	9,355.55	1.25	9,396.42	0.82	9,437.06	0.39
CO [kg]	120.31	116.73	2.97	117.9	2	118.66	1.37
NO_x [kg]	20	19.77	1.14	19.93	0.37	20.01	-0.05
PM_x [kg]	452.33	447.08	1.16	450.17	0.48	452.14	0.04

6.2 Space-time congestion analysis

Space-time diagrams provide visualisation of traffic behaviours over time and space (throughout the observed motorway network). Thus, the spatiotemporal distribution of congestion is shown in *Figure 8*. The speeds in *Figures 8a, 8c, 8e and 8g* are colour coded (from dark red for 0 km/h to dark blue for the vehicle speed around the nominal speed limit (120 km/h)). The x-axis represents the distance measured from the beginning of the motorway sections x=0 to x=8 km corresponding to the length of the simulated motorway stretch. The on-ramp r_3 is located at x=5.4 km. On the y-axis is time and the simulation lasts 1.5 h. *Figure 8a* depicts vehicle speed for the baseline No VSL case. The region with the pattern of yellow and red corresponds to a congestion area in which case vehicles travel with lower speeds. Due to the changes in entering flow intensity at the on-ramp, the floating merge point location of the on-ramp and mainstream vehicles may differ over time [6]. Thus, the bottleneck formation in our experiment occurs at the merge area from x=5.4 to 5.65 km. The congestion starts at t=0.45 h with an activation of the bottleneck (traffic breakdown phenomenon) within the merge area and it propagates upstream up to the position x=4.5 km. After traffic demand decreases, the congestion reduces, and it finally dissolved approximately at t=1.25 h. The best result is achieved with the configuration 300-300-100 (*Figure 8e*) where the congested area is the smallest compared to other configurations.

As the speeds and densities are correlated macroscopic variables (fundamental speed-density diagram) similar patterns with orange-red representing higher density value (congested traffic) can be seen in *Figures 8b, 8d, 8f and 8h*. Observing those graphs vertically near the position of the on-ramp r_3 (merge area from x=5.4 to 5.65 km) it can be seen that the bottleneck is starting to be active at approximately t=0.45 h in which case the density value is around 35 veh/km/lane (light blue stripes in the mentioned graphs).

6.3 Discussion

As seen in *Figure 8*, the traffic breakdown caused by the simulated high traffic demand is inevitable after which the traffic flow went into the unstable congested state. Thus, no matter which VSL configuration is taken, SPSC-VSL cannot prevent the congestion. In the fundamental diagram, this is the condition where the traffic density is above the so-called critical density (see *Figure 1*) characterised by the lower operational capacity of the affected motorway section (active bottleneck).

In the case of the best VSL configuration 300-300-100, the lengths of the VSL zones (VSL1= VSL2=300 m) and appropriate speed limits (see *Figures 9a and 9b*) are sufficient to reduce the traffic outflow from the VSL application zones, which eventually relieves the downstream bottleneck. At the same time, the acceleration area of 100 m is sufficient to ensure that vehicles leaving the VSL zone can accelerate and enter the bottleneck at the critical speed (at which capacity is reached [6]). Consequently, the discharge of the bottleneck is more efficient than other VSL zone configurations, resulting with best congestion dissolving. It should be noted that our experiment differs from the one in [6], where the lowest possible speed limit is 10 km/h, while the nominal speed is 100 km/h. Therefore, it is shown in [6] that the length of the acceleration area below 175 m is not sufficient to ensure enough distance for the vehicle to reach the critical speed at the bottleneck when very low speed limits are applied. Since our lowest speed limit is 60 km/h, the

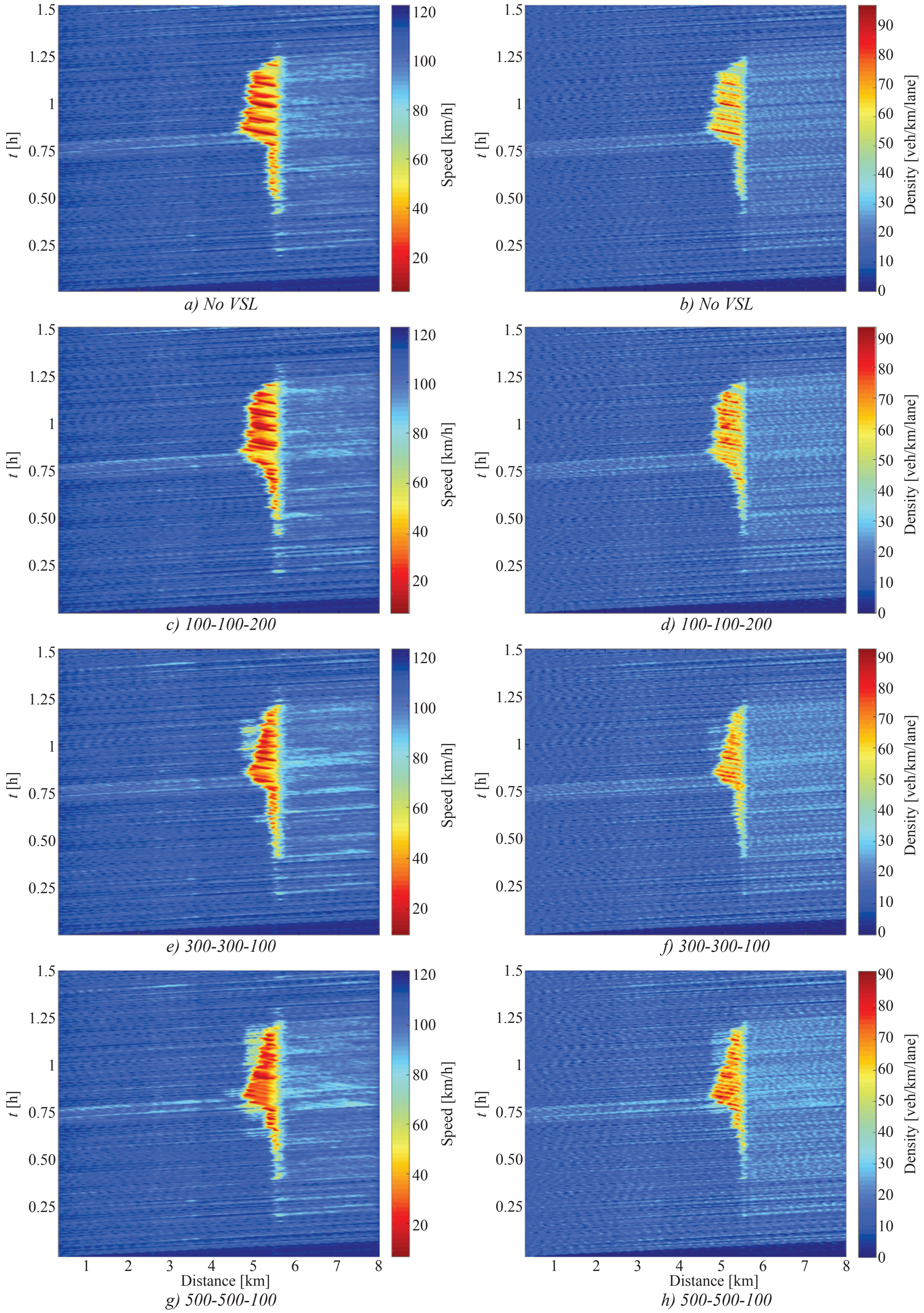
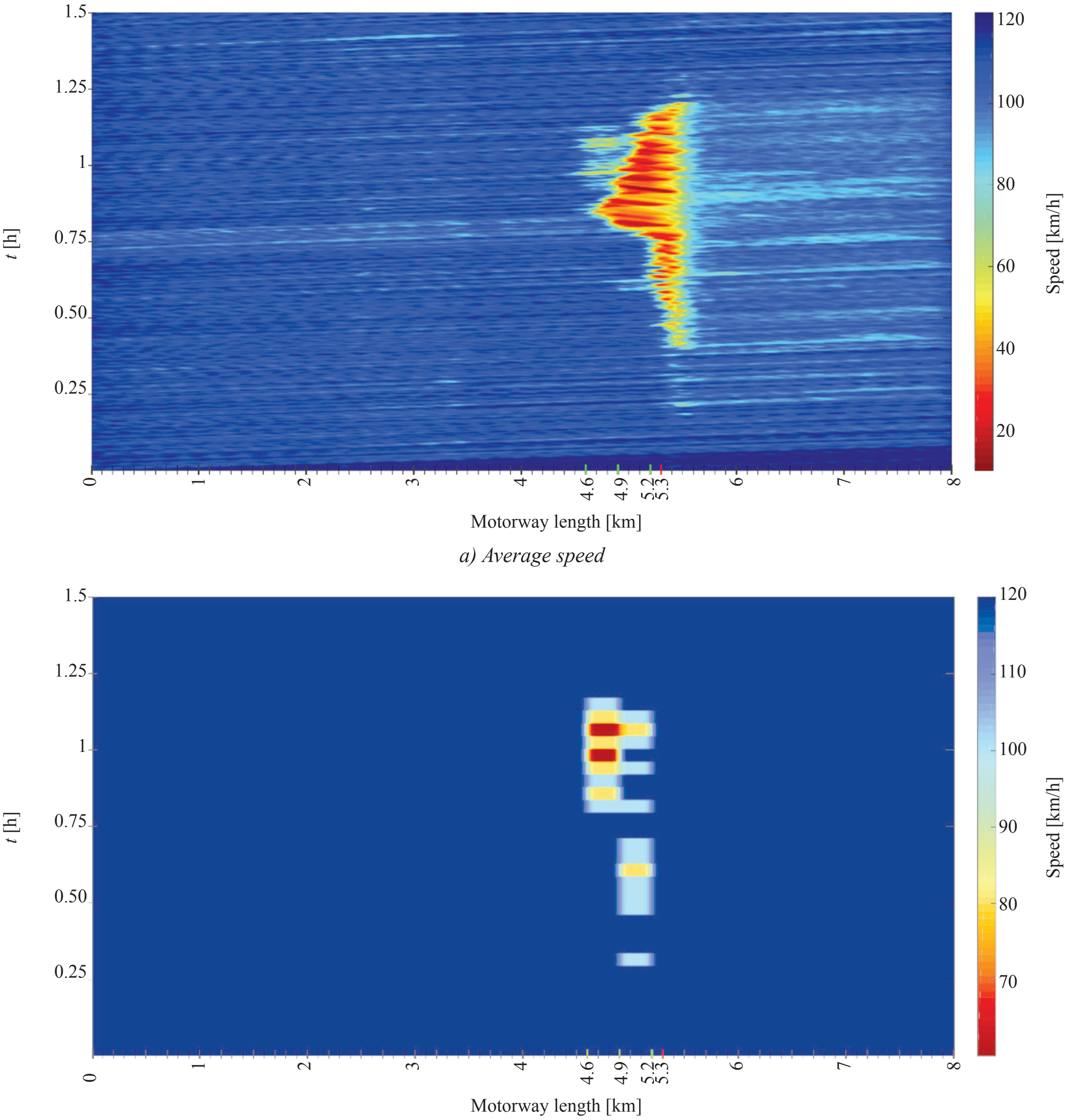


Figure 8 – Space-time diagrams for best obtained VSL configurations



a) Average speed

b) Speed limits

Figure 9 – The best VSL configuration 300-300-100

acceleration area length of 100 m is still sufficient for vehicles to accelerate and reach the bottleneck at the critical speed.

In contrast, with a longer acceleration area, some of the vehicles might accelerate and achieve speed above the critical speed just before they enter the bottleneck. Thus, the discharging effect of the bottleneck is sub-optimal. As a result, the congestion has a longer duration and spreads much more upstream regarding the mainstream flow. Moreover, in the 500-500 VSL zones configuration, the VSL zones lengths are too long, and the vehicles that are slowed down by the VSL travel longer. Consequently, the TTS is higher, although the density and the measured speeds are improved within the bottleneck area (since the VSL controller reacts to congestion in the bottleneck area - section L3). This fact implies that there exists a VSL zone configuration in which both the travel time of the downstream bottleneck and the travel time of the upstream traffic flow affected by VSL zones are minimized efficiently to improve the TTS of the entire motorway system. The recent results in [14] show that the use of longer VSL application areas implies the use of longer acceleration areas in the case of the high-speed limits values. Thus, further research on a control structure adjusting the VSL zones configurations (more spatial variation) in the SPSC-VSL case is desirable.

A positive impact of VSL on one aspect of traffic flow (TTS, average speed and density) is correlated with environmental characteristics (vehicle emissions). As a result, the existing road infrastructure can be complemented by ITS services (like VSL) to make motorway traffic more energy-efficient, thus, fostering a sustainable transportation system in general.

7. CONCLUSION AND FUTURE WORK

This paper analysed the influence of different VSL zones lengths and their distance from the bottleneck location (acceleration zones lengths) on bottleneck control on urban motorways. Obtained results verified that for a given set of available VSL applications and acceleration zones lengths, at least one VSL configuration gives superior performance among others for a given traffic scenario. Thus, it is worthy of creating a VSL system with the possibility of changing the VSL application and acceleration areas to efficiently cope with the unpredictable spatio-temporal varying congestion, which is more likely to be the case in a real traffic scenario. We also examined the calibration of SPSC-VSL regarding the gain parameter and the activation threshold of the controller finding the best values.

Simulation results also highlighted interesting future work directions. Firstly, finer partitioning of VSL application and acceleration zones for controlled motorway sections should be examined, and the effect of more consecutive VSL zones needs to be studied. Secondly, finer scaling of controller gain parameter and activation threshold will be further investigated. We also plan to implement a gain scheduling mechanism for SPSC-VSL together with a finer action space. Finally, more complex real traffic demand patterns and simulation model calibration will also be considered to confirm SPSC-VSL extended applicability regarding a real-world motorway traffic scenario.

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UTJECAJ RAZMJEŠTAJA ZONA OGRANIČENJA BRZINE NA SUSTAV UPRAVLJANJA PROMJENJIVIM OGRANIČENJEM BRZINA NA GRADSKIM AUTOCESTAMA

SAŽETAK

Pristupi upravljanju prometa, posebice promjenjivo ograničenje brzine, često se proučavaju kao rješenja za poboljšanje razine usluge na gradskim autocestama. Međutim, učinkovitost VSL jako ovisi o prostorno-vremenskom rasporedu zona promjenjivog ograničenja brzine. Ključno je odrediti duljinu i lokaciju zona za najbolju učinkovitost sustava promjenjivog ograničenja brzine prije implementacije u stvarni sustav jer optimalna duljina zona i njihova udaljenost od uskog grla izravno utječu na dinamiku prometa, a time i na upravljanje uskim grlom na autocesti. Stoga smo u ovom istraživanju analizirali različite duljine zona promjenjivog ograničenja brzine i njihove pozicije korištenjem jednostavnog proporcionalnog regulatora brzine zatvorene petlje za upravljanje promjenjivim ograničenjem brzine. Procjenjujemo različite konfiguracije zona i njihov utjecaj na kontrolu prometnog toka i emisije vozila u mikroskopskom simulatoru prometa SUMO na scenariju velike prometne potražnje. Rezultati podupiru zapažan-

ja prethodnih istraživača o značajnoj ovisnosti položaja zona primjene ograničenja brzine na učinkovitost sustava promjenjivog ograničenja brzine. Dodatno, dani su novi dokazi o učinkovitosti testiranog regulatora i njegovog dizajna temeljeni na podacima (prometni parametri i emisija vozila) u pogledu najboljeg postavljanja uzastopnih zona promjenjivog ograničenja brzine za upravljanje uskim grlom na autocesti koji nisu analizirani u prethodnim istraživanjima.

KLJUČNE RIJEČI

inteligentni transportni sustavi; upravljanje prometom; promjenjivo ograničenje brzine; gradske autoceste; zone ograničenja brzine i ubrzanja.

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