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Analysis of a cooperative variable speed limit system using microscopic traffic simulation

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ABSTRACT

Variable speed limit systems where variable message signs are used to show speed limits adjusted to the prevailing road or traffic conditions are installed on motorways in many countries. The objectives of variable speed limit system installations are often to decrease the number of accidents and to increase traffic efficiency. Currently, there is an interest in exploring the potential of cooperative intelligent transport systems including communication between vehicles and/or vehicles and the infrastructure. In this paper, we study the potential benefits of introducing infrastructure to vehicle communication, autonomous vehicle control and individualized speed limits in variable speed limit systems. We do this by proposing a cooperative variable speed limit system as an extension of an existing variable speed limit system. In the proposed system, communication between the infrastructure and the vehicles is used to transmit variable speed limits to upstream vehicles before the variable message signs become visible to the drivers. The system is evaluated by the means of microscopic traffic simulation. Traffic efficiency and environmental effects are considered in the analysis. The results of the study show benefits of the infrastructure to vehicle communication, autonomous vehicle control and individualized speed limits for variable speed limit systems in the form of lower acceleration rates and thereby harmonized traffic flow and reduced exhaust emissions.

1. Introduction

Traffic congestion on motorways is a common problem in many countries around the world. The increasing traffic flows result in various problems related to safety as well as system efficiency. Another problem that is receiving more and more attention is the energy and environmental impacts of road traffic congestion, including excess fuel consumption and pollutant and greenhouse gas exhaust emissions.

Today, extensive efforts are focused upon solving problems related to congestion on motorways by applying a wide range of Intelligent Transport System (ITS) technologies to manage and control traffic flows. One commonly used motorway control strategy is a variable speed limit system (VSLS) where variable speed limit signs are linked together via a decision algorithm often based on local speed or flow. VSLSs are often, together with functions such as lane closure and queue warning, included in motorway control systems (MCSs). The purpose of a VSLS is to make drivers aware of current conditions, leading

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to a decrease in accidents and an increase in traffic efficiency. Evaluations of already implemented VSLS in the UK (Highway Agency, 2007) and the Netherlands (van den Hoogen and Smulders, 1994) indicate benefits in terms of safety, system efficiency and reduced exhaust emissions.

Recent advances in communication technology have opened up new perspectives for the development of ITS that utilize vehicle to vehicle (V2V), vehicle to infrastructure (V2I) and infrastructure to vehicle (I2V) communication, so called cooperative systems. The general expectation is that cooperative systems will improve safety and efficiency and reduce the environmental impacts of road traffic in an even more efficient manner than the existing ITS.

The aim of this paper is to study the potential benefits of infrastructure to vehicle communication, autonomous vehicle control and individualized speed limits for variable speed limit systems. We do this by proposing such a cooperative VSLS (C-VSLS) as an extension to an existing VSLS. The proposed C-VSLS builds upon the ideas introduced by Grumert et al. (2013) and Grumert and Tapani (2012, 2013). By I2V communication the variable speed limits are communicated to the vehicles before the variable message signs become visible to the drivers. The C-VSLS is designed as an autonomous speed control system that controls the speed of individual vehicles based on the variable speed limit, the speed of the vehicle and the distance to the variable speed limit sign in front of the vehicle. Controlling the speed of individual vehicles at an earlier stage leads to the hypothesis that the C-VSLS will result in flow harmonization and thereby a reduction in environmental impacts compared to the standard VSLS. To test this hypothesis, a study combining microscopic traffic simulation and an exhaust emission model has been conducted. The contribution of the paper is an estimation of the size of potential benefits, in terms of traffic performance and exhaust emissions, of extending existing motorway VSLSs with I2V communication, autonomous vehicle control and individualized speed limits. The sensitivity of the performance of the C-VSLS to different system settings and traffic penetration rates is considered. The effect of the individualized speed limits of the C-VSLS, and the sensitivity of the effects of the VSLS with respect to different assumptions regarding drivers' ability to read the speed limit signs in front of the vehicles, have been evaluated.

The remainder of the paper is organized as follows. In the Section 2, reviews are presented of existing studies of VSLS and of exhaust emission models. In Section 3, we introduce the C-VSLS and describe the speed control algorithm of the system. The method of the simulation study to evaluate the proposed C-VSLS is presented in Section 4, including the utilized microscopic simulation tool and the emission model adopted. Computational results comparing the C-VSLS to the original standard VSLS are presented in Section 5. Finally, conclusions from the study and directions for further research are discussed in Section 6.

2. Literature review

Evaluations of already implemented VSLS have been performed as field-tests and by the use of traffic simulation. Using traffic simulation, studies prior to implementation can be made of new control algorithms, as well as other improvements of existing systems. Section 2.1 presents some of the published field-tests and simulation based evaluations of VSLSs. The choice of exhaust emission model is of importance in studies of ITS such as the C-VSLS. It is necessary that the emission model used is able to reflect the effects of the traffic and system dynamics on the resulting emissions. A short review of existing exhaust emission models is presented in Section 2.2.

2.1. Variable speed limit systems (VSLSs)

VSLSs have already been implemented in many countries with various functionalities depending on the purpose of the system, the location, etc. Examples of implemented VSLSs include the before mentioned systems in the UK (Highway Agency, 2007) and the Netherlands (van den Hoogen and Smulders, 1994). Studies of these systems indicate benefits in terms of road safety and traffic efficiency, with harmonized traffic flows, more homogenous headways and decreased variance in speed. Concerning the environmental impacts, the system implemented on the M25 in the UK has resulted in reductions of exhaust emissions by 2–8%, depending on type of emission (Highway Agency, 2007). In addition, a state-of-the-art study on systems implemented in Germany, the Netherlands and the UK shows results for Germany and the Netherlands that are in line with the findings in the UK, with harmonized flows as the most highlighted benefit (Smulders and Helleman, 1998). No significant improvements could be concluded on congestion, throughput and capacity in this study. Both advisory and compulsory variable speed limits can be used in a VSLS. A study on the Swedish VSLS indicates however that the effects, when using only advisory speed limits, are very limited (Nissan and Koutsopoulos, 2011).

Besides field tests, one direct way to study VSLS is by the use of traffic simulation. Traffic simulation may lead to a less costly evaluation of existing systems, but more importantly, it will be possible to evaluate systems that are not yet implemented. Numerous studies have been conducted on variable speed limits and VSLS using traffic simulation, resulting in good indications on the general system performance. Whereas most of the simulation studies have been focusing on safety, see e.g. Abdel-Aty et al. (2006), Allaby et al. (2007), Lee et al. (2006), Hellinga and Mandelzys (2011) and Piao and McDonald (2008) and efficiency, see e.g. Papageorgiou et al. (2008) and Torday et al. (2011), few simulation-based evaluations of VSLS that consider environmental impacts have been found in the literature. One exception is the evaluation of impacts of VSLS on air pollution presented by Torday et al. (2011). Most of the studies presented above are based on microscopic traffic simulation, with one exception, Papageorgiou et al. (2008), where macroscopic traffic simulation was used.

Abdel-Aty et al. (2006), Allaby et al. (2007) and Lee et al. (2006) focus on evaluation of different control strategies for VSLS with respect to their effect on safety. Lee et al. (2006) show that control strategies including accurately estimated speed on the road have greater effect than systems using predefined speed limits. This highlights the importance of having good strategies for choosing speed limits to harmonize the flow and also that the closer the speed limit is to the actual speed on the road the better. Although this is of course not the case when an incident has occurred, causing very low speed situations at the controlled area. Control strategies are also considered by Papageorgiou et al. (2008), with emphasis on the effect on traffic efficiency subject to preservation of road safety and environmental impact.

Torday et al. (2011) concluded that the benefits from the systems are largely dependent on the traffic volume. During moderate and high volumes, the systems tend to have more impact. However, the benefits of VSLS are negligible in highly congested conditions. The effects of variations in the driver compliance to the VSLS have also been investigated by Hellinga and Mandelzys (2011). It was concluded that safety is positively correlated with compliance whereas travel time is negatively correlated with compliance. This is in line with other studies, performed by Allaby et al. (2007); Lee2006, showing that when designing control strategies one has to consider a trade-off between safety and travel time.

To our knowledge, few studies exist on the potential benefits of a C-VSLS where I2V communication is introduced as an extension to a current system, especially not with respect to the environmental impacts of the system. A system related to the C-VSLS studied in this paper is considered by Piao and McDonald (2008) where the safety effects of a VSLS combined with an in-vehicle application are discussed.

2.2. Exhaust emission models

Assessment of the environmental impact of road transport requires quantification of vehicle pollutant and greenhouse gas emissions and fuel consumption. The current vehicle emission models can generally be classified into aggregate and microscopic models. Aggregate models, such as ARTEMIS/HEBEFA (Keller and Kljun, 2007), MOBILE6 (Vallamsundar and Lin, 2011; EPA, 2003) and COPERT4 (EEA, 2013) are based on the trip average speed and a set of traffic situations to predict emissions. They are intended for emission inventory of large road networks, or for evaluation of the impacts of infrastructure projects, for which macroscopic or mesoscopic traffic models can be used to estimate average speeds. Aggregate emission models are therefore not sensitive to variations in vehicular instantaneous speed and acceleration, which can have a major effect on the emissions and fuel consumption (Int Panis et al., 2006).

Microscopic emission models can be applied to evaluate the impacts of real-time applications on emissions on a microscale, for example in a congested highway section or an urban street or at road junctions where vehicle operating modes are queuing, accelerating and decelerating rather than steady cruising, microscopic emission models can be applied. Such microscale emission models predict emission rates based on the instantaneous speed profiles and vehicle operating factors such as the engine parameters. Microscopic emission models can be classified into modal and statistical approaches. Modal microscale models e.g. CMEM (Barth et al., 2000) and MOVES (Vallamsundar and Lin, 2011; EPA, 2010) consider the modal operation of the vehicle, i.e. idle, steady-state cruise and various levels of acceleration, and are based on detailed physical analysis of the emission production process to predict instantaneous emissions as a function of the driving modes. Statistical microscale models, e.g. Lei et al. (2010), predict instantaneous emission rates though regression models including speed, acceleration, their product and dummy variables for the driving modes.

The potential benefits of a C-VSLS, i.e. flow harmonization and decreased emission rates, will be highly dependent on the acceleration rates of the vehicles in the traffic flow, and will therefore require a microscopic emission model. The microscopic emission model CMEM is frequently used in studies for evaluation of emission levels, see e.g. Yang and Jin (2014), Lima et al. (2013), Ma et al. (2012) and Zhang et al. (2011). Also, integrating CMEM with a microscopic traffic simulator for estimation of emission rates has been proven useful in several studies, see e.g. Yelchuru et al. (2011), Stevanovic et al. (2009), Boriboonsomsin and Barth (2008), Chen and Yu (2007) and Noland and Quddus (2006). We therefore apply CMEM for the emission analysis in this paper.

3. A cooperative VSLS

The VSLS function included in the Stockholm and the Dutch MCSs (van Toorenburg and de Kok, 1999) is used as reference system for the proposed C-VSLS. The VSLS function consists of detectors measuring mean speed on the road, and variable message signs showing recommended or compulsory speed limits based on the measured speed. If the mean speed goes below a certain threshold, new lower speed limits are shown on the variable speed limit signs. Not only the speed limit sign closest to the detection point show a lower speed limit, a number of speed limit signs further upstream are also showing lower speed limits. To avoid sudden changes in speed limit from one road segment to the next the speed limits shown on signs upstream of the detection point are higher than the speed limit shown on the sign at the detection point.

In the existing VSLS, variable message signs are used for showing information about the speed limits to the drivers. A C-VSLS can be created by having the variable message signs functioning as roadside units, sending out information to the individual vehicles about speed limits via an I2V communication channel. The speed limits given to the vehicles are calculated based on the distance between the vehicle and the speed limit sign showing the new speed, the current speed of the vehicle and the reference speed shown on the speed limit sign. As a result of this approach, when the vehicles reach the new speed limits they have been given individual speed limits at predefined time intervals resulting in a smooth change in speed towards the new speed limit. The speed limits for the VSLS are assumed to be compulsory and the C-VSLS is assumed to be implemented in a future system where vehicles adapt to the individual speed limits without interaction of the driver. The differences between the standard VSLS and the C-VSLS can be summarized in the following bullets:

- With the C-VSLS, information about the variable speed limit is received at an earlier point in time.
- With the C-VSLS, vehicles are given individual speed limits determined by their current speed and position.
- The C-VSLS is assumed to be implemented as an autonomous vehicle control system, i.e. no driver response is necessary to adapt to the individual speed limits. This is achieved by assuming a future system where vehicles adapt to the individual speed limits without interaction of the driver.

The C-VSLS proposed in this article is an extension of a previous introduced C-VSLS (Grumert and Tapani, 2012, 2013; Grumert and Tapani, 2013). We here assume autonomous vehicle control, compared to the earlier studies where speed limit information were given to the driver, who had to react to the given individual speed recommendations. The C-VSLS algorithm has also been modified compared to the earlier papers to prevent accelerations outside of the drivers' desired acceleration and deceleration, and a lower and upper bound has been introduced for the individual speeds given to the vehicles.

For both the VSLS and the C-VSLS, the maximum allowed speed on the road is assumed to be 120 km/h. In the current VSLS system, the mean speed at the detectors is calculated by the use of a smoothed harmonic mean speed given by

$$1/\tilde{v}_{t+1} = \alpha \cdot 1/v_{measured} + (1-\alpha) \cdot 1/\tilde{v}_t, \tag{1}$$

where $\tilde{v}_t$ is the calculated mean speed at time t, $v_{measured}$ is the measured speed at the detectors and α is the smoothing parameter between 0 and 1 (van Toorenburg and de Kok, 1999). A smoothing parameter of 0.25 is used to take into account approximately the 4 last vehicles. If the mean speed at a detector goes below a certain threshold, which is set to 45 km/h, the speed limit is updated. The speed limit sign at the point where the detected mean speed is below the threshold is set to 60 km/h and the following two speed limit signs upstream of this detector are set to 80 km/h and 100 km/h, respectively. If the mean speed at a detector where the variable speed sign shows 60 km/h goes above a certain threshold, which is set to 55 km/h, the speed limit is updated to 120 km/h. Also the two speed limit signs upstream of the congested area, showing lower speed limits, are updated to 120 km/h at the same time. The speed limits and the thresholds are based on a study of the existing MCS and the new speed limit system that is currently being implemented in Sweden (Lind and Strömgren, 2011). It is assumed that the most restrictive lane is regulating the speed limit, i.e. the lane with the lowest mean speed is considered when determining the speed limit for all lanes. The variable speed limits are updated every 4 s. Since the aim of the paper is to quantify the effects of infrastructure to vehicle communication, autonomous vehicle control and individualized speed limits for variable speed limit systems, we assume that all vehicles follow the given speed limits and that all drivers are able to read the speed limit signs within a range of 150 meters.

For the C-VSLS, the variable speed limits are used as reference speeds used to calculate the individual speeds that are given to the vehicles at specific points in time. The vehicles are assumed to receive updates of the speed limit information via communication with the roadside units during the whole road segment between consecutive variable speed limit signs. The individual speed limits given by the C-VSLS to the vehicles are calculated based on the equations of motion. First, the acceleration needed to adapt to the given speed limit at the position of the next variable speed limit sign, $a_{t,i}$, is determined.

$$a_{t,i} = \left(v_{t,j}^2 - u_{t,i}^2\right)/(2 \cdot s_{t,ij}), \tag{2}$$

where $v_{t,j}$ is the speed limit obtained from variable speed limit sign j (located immediately in front of vehicle i) at time t, $u_{t,i}$ is the current speed of vehicle i and $s_{t,ij}$ is the distance between vehicle i and variable speed limit sign j. The acceleration is bounded to the interval between the drivers' maximum desired acceleration and deceleration. The acceleration, given by Eq. (2), is then used to determine the individual speed, $\tilde{w}_{t,i}$.

$$\tilde{w}_{t,i} = u_{t,i} + a_{t,i} \cdot T, \tag{3}$$

where T is the time interval between updates of the individual speed in the C-VSLS. To prevent low speeds, the individual speeds given to the vehicles are never below the current variable speed limit. Similarly, individual speeds above the maximum speed limit on the road are not given to the vehicles. The final individual speed, $w_{t,i}$, is therefore given by

$$w_{t,i} = \max\left(v_{t,j}, \min\left(\tilde{w}_{t,i}, V_{max}\right)\right), \tag{4}$$

where V_{max} is the maximum recommended speed set to be the maximum allowed speed on the road.

4. Method

Earlier studies have shown that VSLS have a potential to improve traffic efficiency. There are also indications of benefits in the form of reduced environmental impacts. A C-VSLS using I2V communication and autonomous vehicle control can be expected to contribute with additional improvements in these areas. To explore this potential we perform a microscopic traffic simulation and emission model based analysis comparing the C-VSLS to the corresponding standard VSLS.

4.1. Traffic simulation modeling of the variable speed limit systems

Microscopic traffic simulators describe individual vehicles in the traffic stream, allowing for control of single vehicles within the simulation. A microscopic traffic modeling approach is therefore deemed suitable for studying the C-VSLS. In this study, we use the open-source microscopic traffic simulation tool, Simulation of Urban MObility (SUMO) (SUMO, 2013; Krajzewicz, 2011). The current version of the model is multi-modal, space continuous and time discrete.

In SUMO, the default car-following model, developed by Krauß (1998), parallels the underlining approach of the Gipps model (Gipps, 1981), in which braking distances are the main consideration. In SUMO the maximum safe speed of a vehicle is described by

$$v_{safe}(t) = v_l(t) + ((g(t) - g_{des}(t))/\tau_{des}), \tag{5}$$

where v_l is the speed of the leading vehicle, $g(t)$ is the gap between follower and leader, $g_{des}(t) = v_l \cdot \tau$ is the follower's desired gap to the leader, where τ is the reaction time of the follower, and τ_{des} is the desired relaxation time calculated as $\tau_b + \tau$, where $\tau_b = \bar{v}/b(\bar{v})$. $\bar{v}$ is the average speed of the leader and the follower and $b(\bar{v})$ is the desired deceleration function.

The desired speed for each individual vehicle at each time step t, $v_{des}(t)$, is taken as the minimum of the maximum speed of the vehicle v_{max}, the speed using the vehicle's maximum acceleration ability $a(v)$, and the safe speed, i.e.

$$v_{des}(t) = \min\left(v_{max}, v(t) + a(v)\Delta t, v_{safe}(t)\right), \tag{6}$$

where Δt is the simulation time step.

A difference compared to the original Gipps-model is the assumption that the driver is not perfect in holding its desired speed (Ranjitkar et al., 2005). This driver imperfection is modeled as a stochastic deceleration. The final speed for the individual vehicles, and at each time step in the simulation, is given by

$$v(t + \Delta t) = \max\left(0, v_{des}(t) - r \cdot a(v) \cdot \epsilon\right), \tag{7}$$

where r is a random disturbance parameter and ϵ is the driver imperfection. r is uniformly distributed between 0 and 1 and ϵ is an input parameter between 0 and 1 depending on the degree of imperfection. The VSLS and C-VSLS are modeled by modifying the maximum speed v_{max} in Eq. (6). At each time step, the variable speed limits for the VSLS or the individual speed limits for the C-VSLS are given to the vehicles in the simulation by replacing Eq. (6) with:

$$v_{des}(t) = \begin{cases} \min\left(v_{t,j}, v(t) + a(v)\Delta t, v_{safe}(t)\right), & \text{VSLS} \\ \min\left(w_{t,i}, v(t) + a(v)\Delta t, v_{safe}(t)\right), & \text{C} - \text{VSLS} \end{cases} \tag{8}$$

where $v_{t,j}$ is the variable speed limit for standard VSLS at location j and $w_{t,i}$ is the individual speed limit for vehicle i.

The SUMO traffic control interface (TraCI) is used to get access to information in the SUMO simulation engine during the simulation runs. Python code is used to communicate with SUMO and for implementation of the VSLS and the C-VSLS.

The network, demand and parameter files are produced separately and communicated to SUMO at the start of a simulation. During the simulation the TraCI is used to communicate speed from the detectors, and to keep track of individual vehicles' speed and position for the C-VSLS. The new maximum allowed speed for the VSLS and the C-VSLS are calculated in the python script based on the detector and individual vehicle data. Finally, the new maximum allowed speed is communicated to SUMO via the TraCI and used in SUMO for calculating the desired speed in the car following model.

4.2. Estimation of exhaust emissions

The micro-scale emission model CMEM is used for estimation of exhaust emissions based on the resulting vehicle trajectories from SUMO. CMEM is a load-based micro-scale model estimated using chassis dynamometer data (Scora and Barth, 2006). The model calculates second-by-second tailpipe emissions as a product of three parameters

$$e_{tailpipe} = r_{fuel} \cdot i_{em/fuel} \cdot C_{pass}, \tag{9}$$

where r_{fuel} is the fuel rate, $i_{em/fuel}$ is the engine-out emission index and C_{pass} is the catalyst pass fraction. The output emissions given by CMEM are HC, NO_x, CO, CO_2 and fuel consumption. In the analysis presented in this paper we choose to present HC, NO_x, and CO_2 emissions. The reason for this choice is that the CO emission of modern engines is limited and that fuel consumption is strongly correlated with the CO_2 emissions.

The vehicle specific parameters used in CMEM have been adopted for emission estimation based on the properties and assumptions of the vehicles simulated in SUMO, i.e. the vehicles are assumed to be of the normal emitting catalyst equipped gasoline fueled passenger car type in CMEM.

4.3. Traffic scenario

An open traffic system consisting of a stretch of motorway, without on- or off-ramps and made up by three lanes, is used to study the effects of the C-VSLS. The reason for choosing this elementary design is to be able to easily evaluate the benefits of extending existing VSLS with an autonomous vehicle control system including I2V communication. The simulated road is divided into eight 500 meter segments, with one detector and one variable speed limit sign gantry per lane on each segment. The simulation is performed for a 20-min interval, excluding a warm-up period of 5 min to prevent from loading effects. The input flow during that period is held constant at 4400 vehicles per hour, which is approximately 70% of the capacity. In order to get an activation of the VSLS and the C-VSLS an incident is modeled 100 meters upstream of the last detector station. This is done by decreasing the speed on a 100 meter long segment to around 25 km/h after 5 min. The speed decrease is active for 10 min. The effect of this is that the vehicles are slowing down and faster vehicles coming from behind starts to decelerate. This will create congestion moving upstream of the incident area and a queue starts to build up. As a result of the moving congestion one or more of the variable speed limits upstream of the incident area is activated and a comparison of how the C-VSLS and the VSLS behave during active conditions can be made. Fig. 1 gives an illustration of the considered traffic scenario. By modeling the incident in this manner, and not by closing a lane or by the use of an onramp which requires modeling of weaving behavior, the dependence of the results on the lane changing and merging models used in the simulation is limited.

When implementing the VSLS it is assumed that all vehicles follow the given speed limits and that the vehicles are able to read the speed limits shown on the gantries within a range of 150 meters. Approaching vehicles, following the standard VSLS, are updating their maximum allowed speed according to Eq. (8) when located within this range.

For the C-VSLS different update times T can be applied, see Eq. (3). Since the road segments are 500 meter, long update times may result in vehicles that pass more than one variable speed limit sign before the individual speed limit is updated. This is obviously undesirable and T should consequently be chosen sufficiently short so that the individual speed limit is updated in each segment of the road. In this study, three different update times ensuring an update within each segment have been considered ($T = 0.1$ s, 1 s and 10 s). Also two longer update times ($T = 30$ and 60 s) have been considered to see how it will affect the system, even though the purpose with the C-VSLS are partly lost.

When introducing new systems on the market, with a need for new technology and/or equipment, the penetration rates are often low in the beginning. A realistic assumption would therefore be that not all drivers will be equipped with a cooperative system, especially at an early stage of the implementation phase. Different penetration rates of the C-VSLS have been investigated to be able to evaluate the effect of only a portion of the vehicles being equipped with the system.

The C-VSLS using individual speed limits have been compared to a C-VSLS using fixed speed limits, to evaluate the effect on flow harmonization when using different cooperative strategies. For the C-VSLS using fixed speed limits it is assumed that the vehicles are given the variable speed limit applied on the road segment they are on at the moment.

Finally, for the standard VSLS three different assumptions for when the vehicles are able to read the speed limits have been investigated (0, 150 and 300 meters). The distance of 0 meters has been included purely as a hypothetical case for comparison. It is an unrealistic scenario since drivers are likely to read, and react, on the sign before being at the sign.

The vehicle parameters used in the simulation are set to default values used in SUMO version 0.18.0, SUMO (2013), see Table 1, except for the speed deviation and the speed factor. Each vehicle is assigned an individual speed factor, with which

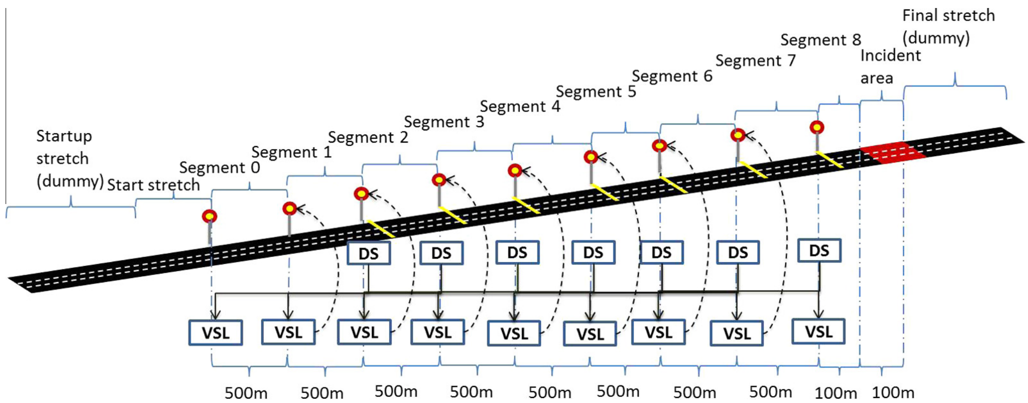

Fig. 1. Illustration of the modeled road and the VSLS (VSL: Variable Speed Limit sign, DS: Detector Station).

Table 1
Vehicle parameter default values used in the simulation (SUMO, 2013).

Parameter name	Definition	Default value
accel	The acceleration ability of the vehicle (m/s^2)	2.6
decel	The deceleration ability of the vehicle (m/s^2)	4.5
sigma	Driver imperfection (between 0 and 1)	0.5
tau	The reaction time of the driver (s)	1
minGap	Empty space after leader (m)	2.5
length	The length of the vehicle (m)	5.0

the maximum speed is multiplied, representing their individual perceived maximum speed. The speed factors are drawn from a normal distribution with mean 1.05 and speed deviation 0.05. The speed of the C-VSLS controlled vehicles is assumed to be autonomously controlled by the system. Vehicles are generated with exponentially distributed headways. The randomness of the simulations performed is taken into consideration by performing 15 replications of the simulation for all simulated scenarios. Acceleration, speed and travel time results are based on vehicle trajectories collected from SUMO during the simulation by use of the TraCI.

5. Computational results

The effects of the proposed C-VSLS are studied by comparing the acceleration distributions, the means and standard deviations of vehicle speeds and the CO_2, HC and NO_x emissions. The acceleration distributions presented are the result of the simulated vehicles' accelerations in each time step and for 15 replications of the simulation. The emissions are summed up over the simulated road and time period. The speed profiles are means over the simulated road and calculated as rolling averages over 30 s intervals of the simulated time period. The presented confidence intervals and standard errors of the means are with respect to 15 replications of the simulation for each scenario.

First, in Section 5.1, the effects of the C-VSLS are compared to the effects of the standard VSLS. Then, in Section 5.2 the sensitivity of the C-VSLS to the system update time is investigated. Scenarios including different traffic penetration rates of the C-VSLS are analyzed in Section 5.3. Finally, in Section 5.4, an investigation on the effect of using individualized speed limits for the C-VSLS is made. The effect of the distance from where the drivers following the VSLS are able to read the speed limits is also considered.

5.1. Comparison between C-VSLS and VSLS

The expectation is that the frequency of high acceleration rates should increase for the VSLS compared to the C-VSLS. This is confirmed by the acceleration rate distributions in Fig. 2. The update time for the C-VSLS is set to the simulation time step, i.e. $T = 0.1$ s.

A two-sample Kolmogorov–Smirnov test of the distance between the two empirical probability distributions confirms that the distributions are different, $p < 0.001$. Both the C-VSLS and the VSLS have accelerations centered around zero, but the VSLS result in higher frequencies of high acceleration rates compared to the C-VSLS and a wider acceleration distribution.

The mean and standard deviation of speeds during the simulated time period for the VSLS and C-VSLS scenarios are presented in Fig. 3. The standard error of the means presented is less than or equal to 0.48 m/s and 0.39 m/s in all points for the mean speed and the mean standard deviation of speed, respectively.

The figures show that the mean speed for the VSLS is slightly below the mean speed for the C-VSLS. As expected, the mean standard deviation of speed is higher for the VSLS compared to the C-VSLS, especially when the systems are inactive. This is a result of the input desired speed distribution and the autonomous vehicle control of the C-VSLS equipped vehicles. When the systems are active the mean standard deviation of speed becomes higher as a result of the differences in speed limits between different segments of the road. There is also a difference in mean standard deviation of speed during the incident when the systems are active, indicating a contribution of the I2V communication part of the C-VSLS.

For the C-VSLS scenario, oscillations appear when the system becomes active. This can be explained by the short update time interval, $T = 0.1$ s, resulting in immediate response, and a degree of over-reaction, to speed limit changes by the vehicles in the simulation.

Table 2 gives an overview of the emissions in the VSLS and the C-VSLS scenarios. The intervals given in the tables are standard normal distribution based confidence intervals at a 95% confidence level.

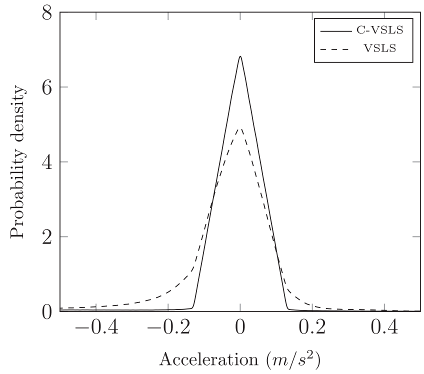

Fig. 2. Empirical acceleration density functions for the VSLS and the C-VSLS scenarios.

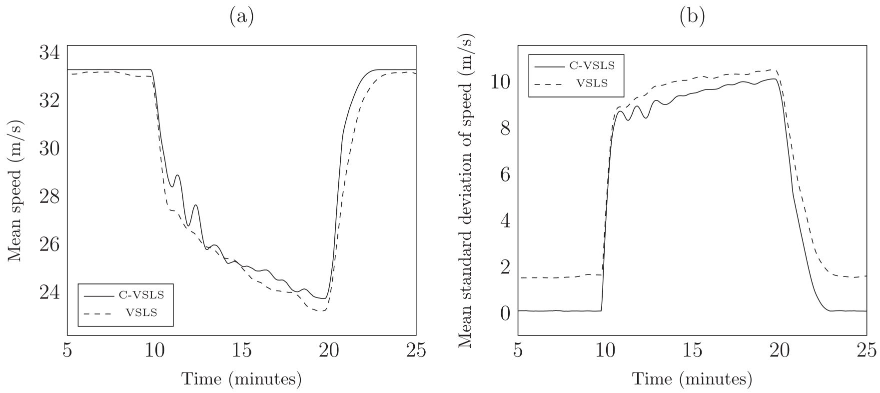

Fig. 3. Mean speed (a) and mean standard deviation of speed (b) on the entire road for the VSLS and the C-VSLS scenarios.

Table 2
Emissions generated in the VSLS and the C-VSLS scenarios. For each type of emission, the mean emission is presented together with the difference between the VSLS and the C-VSLS scenarios.

	CO_2		HC		NO_x	
	Mean (kg)	Diff (%)	Mean (g)	Diff (%)	Mean (g)	Diff (%)
VSLS	1381 ± 12		2164 ± 26		3978 ± 40	
C-VSLS	1359 ± 17	1.6	1834 ± 34	15.3	3605 ± 53	9.4

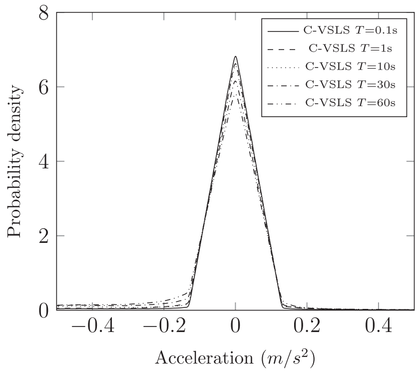

Fig. 4. Empirical acceleration density function for the C-VSLS with update times, 0.1 s, 1 s, 10 s, 30 s and 60 s.

Differences are found between the VSLS and the C-VSLS for all types of emissions presented. The differences are significant for HC and NO_x. For CO_2 the confidence intervals overlap indicating a non-significant difference.

5.2. Effect of the update time of the C-VSLS

The effect of the sensitivity of the C-VSLS to the system update time, T, is investigated by analysis of scenarios with different update times. For $T = 0.1$ s to $T = 10$ s the update times are in the range such that vehicles receive at least one update of the individual speed in each segment of the road. When the update times becomes longer and more than one road segment is passed before the system receive a new update the individual speed limits are not reflecting the speed limits on the road segment in front of the vehicle. Even so, it is interesting to investigate the effect of longer update times.

The distribution of acceleration rates for scenarios with different C-VSLS update times are shown in Fig. 4. We conclude that the C-VSLS is not sensitive to changes in system update time in the range between 0.1 and 10 s. When the updates occurs with an interval less than one update per road segment ($T = 30$ and 60 s) the traffic system is, as expected, less harmonized as the frequency of high accelerations are increased and the frequency of accelerations close to zero are decreased.

The mean speeds and mean standard deviation of speeds during the simulated time period for the scenarios with different update time of the C-VSLS are presented in Fig. 5. The standard error of the means presented is less than or equal to 0.49 m/s, and 0.52 m/s in all points for the mean speed and the mean standard deviation of speed, respectively.

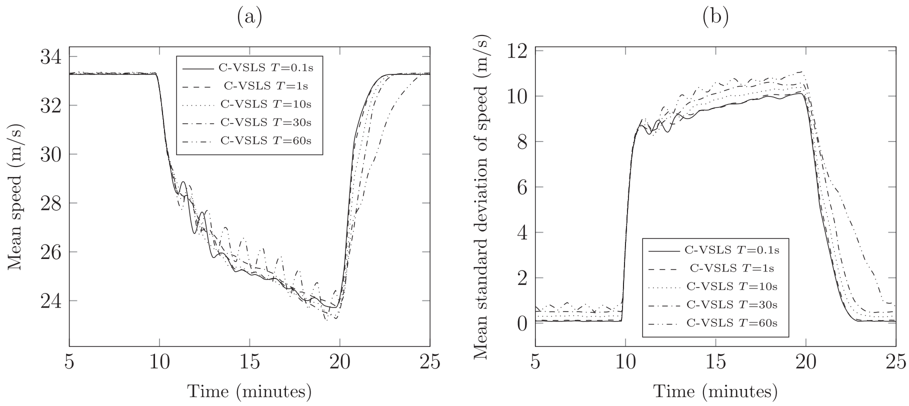

Fig. 5. Mean speed (a) and mean standard deviation of speed (b) on the entire road for the C-VSLS scenarios with different update times, 0.1 s, 1 s, 10 s, 30 s and 60 s.

The oscillations observed when the system becomes active for the update time $T = 0.1$ are decreasing with increasing update time. In other words, by increasing the C-VSLS update time the mean speed is becoming more stable. An update time $T = 0.1$ s seems therefore to be too short. For longer update times the recovery period towards free flow speed are slower. This is intuitive since the longer a vehicle drive with reduced speed limit until getting an update the longer will it take until the traffic system recovers. Also the mean standard deviation of speed is increased as a result of the longer update times. For $T = 60$ s oscillations becomes observable both for the mean speed and the mean standard deviation of speed. This shows that longer update times makes the system unstable.

The emissions for the scenarios with different C-VSLS update times are presented in Table 3. The intervals presented are standard normal distribution based 95% confidence intervals of the means.

There is a tendency for increased emissions with increasing C-VSLS update time. The small effect sizes are in line with the expectations given by the acceleration distributions shown in Fig. 4. Although, for $T = 60$ s the increase in emission rates are noticeably higher compared to the other update times.

We conclude that the C-VSLS is robust to changes in update time with respect to the resulting acceleration rates, vehicle speeds and emissions for update times where an update is received per segment of the road. A very short update time leads to oscillations in speed when the system becomes active. For longer update time there is a tendency to decreased efficiency and a less harmonized traffic system. This is especially observable for $T = 60$ s. Apart from a less harmonized traffic system leading to fluctuations and longer recovery times the purpose of the C-VSLS is lost with longer update times. The reason for this is that the updates are to few to reflect the properties of the system.

5.3. Effect of the C-VSLS penetration rate

Investigation of scenarios including different C-VSLS traffic penetration rates are made by a similar set of comparisons as in Section 5.2. Here an update time of $T = 1$ s is used for the C-VSLS. The reason for choosing this update time is that the results from the previous analysis of the effect of the update time showed that this update time is long enough to prevent oscillations in speed after system activation. It can also be considered feasible to design an I2V communication system with an update time in the order of 1 s.

The expectation is that increasing the C-VSLS penetration rate would result in a more narrow empirical acceleration distribution. The results in Fig. 6 are in line with this expectation.

Two-sample Kolmogorov–Smirnov tests confirm that the difference between all pairs of distributions are significant ($p < 0.001$).

Fig. 7 show the mean speed and the mean standard deviation of speed for the different C-VSLS penetration rate scenarios. The standard error of the means presented is less than or equal to 0.69 m/s and 0.52 m/s in all points for the mean speed and the mean standard deviation of speed, respectively.

Table 3
Emissions generated in the scenarios with different update times of the C-VSLS.

C-VSLS update time T (s)	Mean CO_2 (kg)	Mean HC (g)	Mean NO_x (g)
0.1	1359 ± 17	1834 ± 34	3605 ± 53
1	1360 ± 19	1844 ± 38	3629 ± 62
10	1364 ± 17	1907 ± 39	3693 ± 59
30	1361 ± 18	1919 ± 37	3687 ± 58
60	1373 ± 18	2011 ± 37	3801 ± 58

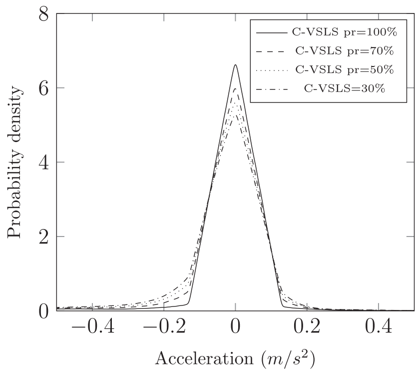

Fig. 6. Empirical acceleration density functions for C-VSLS penetration rates (pr) 100%, 70%, 50% and 30%.

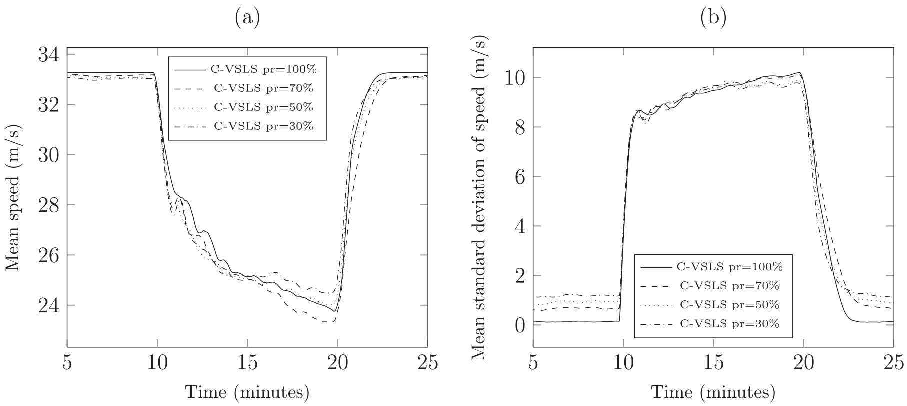

Fig. 7. Mean speed (a) and mean standard deviation of speed (b) on the entire road for scenarios with different C-VSLS penetration rate (pr).

When the system is inactive, before and after the simulated incident, the mean standard deviation of speed becomes higher with lower C-VSLS penetration rates as expected. When the system is active and between time 15 and 20 min, the mean speeds for the 30% and 70% penetration rates scenarios are higher and lower than the mean speed of the 100% penetration rate scenario, respectively. An investigation of the speed distribution on the individual segments of the road reveals that these results are due to equipped vehicles either disturbing or contributing to flow harmonization, depending on the penetration rate. When the difference in desired speed amongst the vehicles is high this can lead to frequent lane changes and this in turn might result in increased congestion on the road. In the 30% penetration rate scenario, most vehicles follow the standard VSLS and the relatively few C-VSLS equipped vehicles contribute to reducing the variance in speed between lanes and thereby the need for lane-changing maneuvers that will disturb the flow. In the 70% scenario, the few non-equipped vehicles will disturb the flow by changing lanes when the C-VSLS equipped vehicles start to decelerate to reach the new speed limit.

Since an increasing C-VSLS penetration rate was found to result in a narrowing of the acceleration distribution the expectation is that it will also lead to a decrease in emissions. The results shown in Table 4 confirms this expectation.

There is a tendency for reduced emissions with increasing C-VSLS penetration rates. Significant effects can be concluded for HC and NO_x between the 100% penetration rate scenario and the other scenarios. Comparing the 30% C-VSLS penetration rate scenario to the 100% scenario, there is a decrease of 10.3 and 6.0% in HC and NO_x emissions, respectively.

We conclude that increasing C-VSLS penetration rates contribute to a narrowing of the acceleration distribution and reduced emissions. Concerning the vehicle speeds, in the studied 30 and 70% penetration rate scenarios, there is an effect of vehicles of the minority in the flow either contributing to or disturbing the flow harmonization effect of the C-VSLS.

Table 4
Emissions generated in scenarios with different C-VSLS penetration rate.

C-VSLS penetration rate (%)	Mean CO_2 (kg)	Mean HC(g)	Mean NO_x(g)
30	1364 ± 17	2056 ± 31	3859 ± 51
50	1363 ± 29	2005 ± 39	3803 ± 63
70	1364 ± 19	1967 ± 43	3759 ± 76
100	1360 ± 19	1844 ± 38	3629 ± 62

5.4. Effect of the individual speed limits for the C-VSLS and visibility of the variable speed limit signs for the VSLS

To determine the effect of the individualized speed limits for the C-VSLS, a C-VSLS with individualized speed limits have been compared to a C-VSLS with identical speed limits for all vehicles. Fig. 8 gives an overview of the acceleration levels for these two different cooperative approaches. It is concluded that there is a tendency for higher frequencies of accelerations around zero for the C-VSLS using individual speed limits compared to the C-VSLS using identical speed limits for all vehicles.

Fig. 8 also includes acceleration distributions for the standard VSLS using three different distances for when the drivers are able to read the speed limit signs. No significant differences are noticed for the different distances. When assuming that the drivers can read the speed limits only when passing the speed limit signs there are somewhat lower frequencies of accelerations around zero.

The mean speeds and mean standard deviation of speeds for the C-VSLS with individual and identical speed limits and for the VSLS using different assumptions regarding when the drivers are able to read the speed limits are shown in Fig. 9. The standard error of the means presented is less than or equal to 0.80 m/s, and 0.69 m/s at all points for the mean speed and the mean standard deviation of speed, respectively.

It is concluded that the C-VSLS using identical speed limits result in somewhat higher mean speed in the beginning of the congested period as a result of vehicles not lowering the speed until reaching the variable speed limit sign. During later stages of the congestion period and during the recovery phase the mean speed is higher for the C-VSLS using individual speed limits compared to the C-VSLS using identical speed limits. This is a result of faster communication to the vehicles of the increased speed limits. But also, since the higher mean speeds are seen during later stages of the congested period, C-VSLS using individual speed limits is more efficient during long time periods of congestion. What is also noticeable is that the mean standard deviation of speed is higher for the C-VSLS using identical speed limits compared to the C-VSLS using individual speed limits, indicating a more harmonized flow with individual speed limits.

The mean speeds and the mean standard deviation of speeds are comparable for different assumptions regarding the distances from when the speed limits are readable. An exception, observable during the recovery phase, occurs when the drivers are unable to read the speed limits until passing speed limit signs. The mean speeds are in line with the C-VSLS using

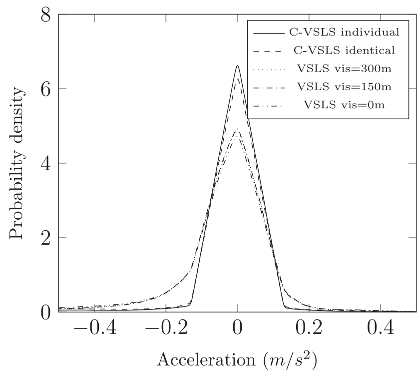

Fig. 8. Empirical acceleration density functions for the C-VSLS with individual and identical speed limits, as well as for the VSLS with different assumptions for the distance when the drivers are able to read the speed limit signs.

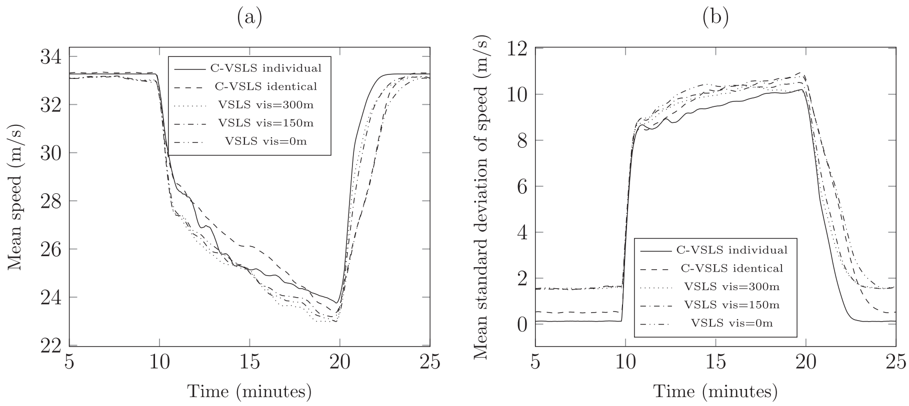

Fig. 9. Mean speed (a) and mean standard deviation of speed (b) on the entire road for scenarios for the C-VSLS using individual and identical speed limits, and for the VSLS with different assumptions for the distance when to read the speed limit signs.

Table 5
Emissions generated in the scenarios for the C-VSLS with individual and identical speed limits, and for the VSLS with different assumptions for the distance when to read the speed limit signs.

C-VSLS update time T (s)	Mean CO_2 (kg)	Mean HC (g)	Mean NO_x (g)
C-VSLS individual	1360 ± 19	1844 ± 38	3629 ± 62
C-VSLS identical	1371 ± 19	1992 ± 52	3768 ± 72
VSLS vis = 300 m	1377 ± 12	2163 ± 32	3968 ± 48
VSLS vis = 150 m	1381 ± 12	2164 ± 26	3978 ± 40
VSLS vis = 0 m	1384 ± 13	2185 ± 32	4002 ± 48

identical speed limits which is the result of the drivers having no information about the upcoming speed limit before passing the speed limit sign in both cases.

As a result of the less harmonized flow for the C-VSLS with identical speed limits, also the emissions are expected to be higher compared to the C-VSLS with individual speed limits. This is confirmed in Table 5. The intervals presented are standard normal distribution based 95% confidence intervals of the means. The differences between the C-VSLS with individualized and identical speed limits are significant for HC (8.0%) and NO_x (3.8%). The emissions for the VSLS with different assumptions for when the vehicles are able to read the speed limit signs are comparable for all distances. For a distance of 0 meter the emissions are somewhat higher especially for HC and NO_x, which probably is a result of the higher mean standard deviation of speed seen in Fig. 9 (b).

This shows that the C-VSLS using individualized speed limits have a greater effect on flow harmonization compared to a system using a simpler strategy only communicating the variable speed limit assigned to each road segment at the time of the speed limit update. Also, using different assumptions for when the drivers are able to read the speed limits does not seem to have a great effect on the results for the standard VSLS. An expectation occur during the recovery phase after the congested period and when assuming that the drivers are able to read the speed limits just when passing the sign.

Effects of VSL system properties have not been considered in this study. Changes in the system properties would however probably have effects on the results. In the considered VSLS, the speed limit is updated based on the measured mean speed. An update of the variable speed limit is based on measurements from at least 12 vehicles and if no vehicle is detected for a period of 30 s, the mean speed is set to 120 km/h for that detector. These settings have an effect on the system performance in non-congested situations when few vehicles, that might have very different free-flow speeds, are detected. But this will be of limited importance for the results presented as the system will be inactive in free-flow conditions. The speed limits are updated every forth second. This can be considered a relatively short update interval. As a result the system responds rapidly to changes in mean speed at the detectors. By increasing the speed limit update interval the system would not be as sensitive to changes in the prevailing traffic conditions and the speed limits might be active for a longer period than necessary, not corresponding to the actual mean speeds. This could have a negative effect on the acceleration levels due to hard breaking in situations when the mean speeds are higher than the speed limits.

The variable speed limits are based on Lind and Strömgren (2011). Lower speed limits would probably result in more frequent higher acceleration rates for both the VSLS and the C-VSLS. A larger difference between the speeds of upstream vehicles and the speed limits on the controlled stretch contribute to this effect. Conversely, higher speed limits would probably result in less frequent high acceleration rates.

6. Conclusions

In this paper we have studied the potential benefits of infrastructure to vehicle (I2V) communication, autonomous vehicle control and individualized speed limits for variable speed limit systems (VSLSs) by proposing a cooperative systems extension (C-VSLS) to an existing VSLS. The effects of the proposed C-VSLS were analysed by comparing the C-VSLS to the corresponding standard VSLS by means of traffic simulation.

The conclusion, based on the results of the simulation experiments, is that I2V communication, autonomous vehicle control and individualized speed limits can contribute to flow harmonization and reduced exhaust emissions. The C-VSLS has been shown to result in a narrowing of the acceleration rate distribution compared to the existing VSLS and reductions in NO_x and HC emissions were established.

The suggested C-VSLS is not sensitive to system update times shorter than a reasonable upper bound, corresponding to at least one update of the individual speed on each segment of the road. For longer update times the system properties are not reflected by the individual speed limits given to the vehicles. This results in a less harmonized traffic system with higher emission rates and oscillating mean speeds and mean standard deviation of speeds, especially for $T = 60$ s. The effect of the C-VSLS is also found to increase with increasing traffic penetration rate of the system. However, in the scenario with a C-VSLS penetration rate of 30%, compared to a penetration rate of 100%, there was an effect on speed when the system was active in the form of increased mean speed. Similar, in the scenario with a C-VSLS penetration rate of 70% compared to a penetration rate of 100%, there was a decrease in mean speed. With a minority of C-VSLS equipped vehicles in the flow the non-equipped vehicles approach the new speed limit areas with higher mean speed and the equipped vehicles contribute to less frequent lane changes with a more harmonized flow and increased speed levels as a result. While by having a majority of C-VSLS equipped vehicles the few non-equipped vehicles, having a higher desired speed tend to change lane more frequent and thereby disturbing the flow, leading to a lower mean speed.

A comparison between the C-VSLS using individual speed limits and the C-VSLS using identical speed limits shows that individual speed limits contributes to a more harmonized flow, which in turn reduces the emissions. Although, in order for the C-VSLS using individual speed limits to be effective the update time is of importance. With frequent update times the vehicles approaches the new speed limits in a smooth way compared to longer update times which results in a more irregular driving style, reducing the effect of using individual speed limits. Also, with an autonomous vehicle control system the drivers does not have to react on the speed updates and should therefor prefer a smoother driving style with more frequent update times. The effect of the VSLS using different assumptions regarding the distances for when the speed limits become readable does not seem to have great effects on the harmonization, mean speed levels and the emissions. Although a decrease of mean speed and an increase of emission rates are seen when the vehicles are assumed to not being able to read the speed limits before reaching the speed limit sign. This can be compared to the C-VSLS using identical speed limits where an update occurs only when the vehicles have passed the speed limit sign. Even so, the C-VSLS using identical speed limits is superior to the VSLS regarding acceleration rates and emission levels.

A possible extension of the study presented in this paper is to integrate the C-VSLS with a cooperative adaptive cruise control system. A system using the vehicles in the traffic stream as probes instead of fixed detector stations could also provide further improvements. Such communication could result in faster and more precise detection of congested traffic states, and the C-VSLS could be designed to adapt to both the variable speed limits on the road and to downstream vehicles. Also, vehicle to infrastructure communication could be considered to improve the variable speed limit system itself.

The aim of this study has not been to find the weaknesses and limitations of the existing VSLSs, but to show the potential of adding infrastructure to vehicle communication, autonomous vehicle control and individualized speed limits to the systems. The results presented will be useful for further exploration of C-VSLSs and further development of current VSLSs. However, one limitation common to many existing VSLSs in operation is that the methods used to determine the variable speed limits are based on simple speed or flow thresholds. The purpose of the speed limit change plays an important role for how much the speed limit should be lowered, i.e. is the purpose to increase efficiency, to increase safety or to reduce emissions. These purposes might not always work together. In the literature, there are more elaborate VSLS control strategies that can be considered e.g. Carlson et al. (2011), Hegyi et al. (2009), Lee et al. (2006). A common denominator of these strategies is better adaptation to the actual conditions on the road. An improved VSLS control strategy will probably also contribute to improved effect of a C-VSLS.

Assumptions regarding the simulation scenario, such as where the incident is located, the reduction in speed limit of the incident is of importance for the results. Also the existing VSLS control strategy could be investigated further by performing a sensitivity analysis with respect to speed limit update times, distance between gantries, the reduction in speed limit etc. By performing sensitivity of the suggested parameters more knowledge about these effects could be gained. This is left as a topic for future research.

The choice of vehicle type is of interest for the effects on the exhaust emissions. By assuming a more diverse vehicle fleet composed by different vehicle types with other emission patterns, different results can be expected. Also, by assuming a vehicle fleet composed by new types of vehicles like electric and hybrid vehicles, in addition to the gasoline vehicles assumed in this study, other emission models might be needed. Since the main aim is to compare the C-VSLS with the standard VSLS this has not been part of this study, but it is an interesting topic for future research.

Finally, the C-VSLS proposed in this paper is based on a simple approach using the equations of motion to model the system and to isolate the effects of I2V communication. More elaborate models could be used to represent the C-VSLS, which could result in greater effects than the once observed here.

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References

Abdel-Aty, M., Dilmore, J., Dhindsa, A., 2006. Evaluation of variable speed limits for real-time freeway safety improvement. Accid. Anal. Prevent. 38 (2), 335–345.

Allaby, P., Hellinga, B., Bullock, M., 2007. Variable speed limits: safety and operational impacts of a candidate control strategy for freeway applications. IEEE Transact. Intell. Transp. Syst. 8 (4), 671–680.

Barth, M., An, F., Younglove, T., Scora, G., Levine, C., Ross, M., Wenzel, T., 2000. Development of a Comprehensive Modal Emissions Model. Final Guide, Project 25-11. Technical Report, National Cooperative Highway Research Program, Washington D.C., U.S.

Boriboonsomsin, K., Barth, M., 2008. Impacts of freeway high-occupancy vehicle lane configuration on vehicle emissions. Transp. Res. Part D: Transp. Environ. 13 (2), 112–125.

Carlson, R., Papamichail, I., Papageorgiou, M., 2011. Local feedback-based mainstream traffic flow control on motorways using variable speed limits. IEEE Transact. Intell. Transp. Syst. 12 (4), 1261–1276.

Chen, K., Yu, L., 2007. Microscopic traffic-emission simulation and case study for evaluation of traffic control strategies. J. Transp. Syst. Eng. Inf. Technol. 7 (1), 93–99.

EEA, 2013. Emep/eea Emission Inventory Guidebook 2013. Technical Report, European Environment Agency, Copenhagen, Denmark.

EPA, 2003. User's Guide to Mobile6.1 and Mobile6.2 Mobile Source Emission Factor Model. Technical Report, United States Environmental Protection Agency, Washington D.C., U.S.

EPA, 2010. Technical Guidance on the Use of Moves 2010 for Emission Inventory Preparation in State Implementation Plans and Transportation Conformity. Technical Report, EPA-420-B-10-023, United States Environmental Protection Agency, Washington D.C., U.S.
Gipps, P., 1981. A behavioural car-following model for computer simulation. Transp. Res. Part B: Methodol. 15 (2), 105–111.
Grumert, E., Tapani, A., 2012. Impacts of a cooperative variable speed limit system. In: Procedia – Social and Behavioral Sciences 43 (8th International Conference on Traffic and Transportation Studies (ICTTS 2012)), pp. 595–606.
Grumert, E., Tapani, A., 2013. Microscopic traffic simulation for evaluation of a cooperative variable speed limit system. In: 1st SUMO User Conference. Berichte aus dem DLR-Institut für Verkehrssystemtechnik, pp. 147–164.
Grumert, E., Ma, X., Tapani, A., 2013. Effects of a cooperative variable speed limit system on traffic performance and exhaust emissions. In: TRB 92nd Annual Meeting Compendium of Papers, Washington D.C., U.S.
Hegyi, A., Hoogendoorn, S., Schreuder, M., Stoelhorst, H., Viti, F., 2009. Specialist: a dynamic speed limit control algorithm based on shock wave theory. In: 11th International IEEE Conference on Intelligent Transportation Systems. IEEE Operations Center, Piscataway, 2008, p. 827.
Hellinga, B., Mandelzys, M., 2011. Impact of driver compliance on the safety and operational impacts of freeway variable speed limit systems. J. Transp. Eng. 137 (4), 260–268.
Highway Agency, 2007. M25, Control Motorway, Summary Report. Technical Report, Department for Transportation, London, UK.
Int Panis, L., Broekx, S., Liu, R., 2006. Modelling instantaneous traffic emission and the influence of traffic speed limits. Sci. Total Environ. 371, 270–285.
Keller, M., Kljun, N., 2007. Artemis, Road Emission Model, User Guide. Technical Report, EU Commission.
Krajzewicz, D., 2011. Traffic simulation with sumo – simulation of urban mobility. In: Barceló, J. (Ed.), Fundamentals of Traffic Simulation, International Series in Operations Research & Management Science, vol. 145. Springer, pp. 269–293, Ch. 8.
Krauß, S., 1998. Microscopic Modeling of Traffic Flow: Investigation of Collision Free Vehicle Dynamics. PhD Thesis, Hauptabteilung Mobilität und Systemtechnik des DLR Köln, Mathematisches Institut, Universität zu Köln.
Lee, C., Hellinga, B., Saccomanno, F., 2006. Evaluation of variable speed limits to improve traffic safety. Transp. Res. Part C: Emerg. Technol. 14 (3), 213–228.
Lei, W., Chen, H., Lu, L., 2010. Microscopic emission and fuel consumption modeling for light-duty vehicles using portable emission measurement system data. World Acad. Sci. Eng. Technol. 66, 918–925.
Lima, E.P., Bertoncini, B.V., Gimenes, M.L., 2013. Simulation of the impact on carbon monoxide concentration resulting from replacing a signalised intersection with a roundabout. Int. J. Environ. Pollution 52 (3), 141.
Lind, G., Strömgren, P., 2011. Säkerhetseffekter av trafikledning och its, litteraturinventering, v0.9. Technical Report, Movea, Stockholm, Sweden.
Ma, X., Lei, W., Andrasson, I., Chen, H., 2012. An evaluation of microscopic emission models for traffic pollution simulation using on-board measurement. Environ. Model. Assess. 17 (4), 375–387.
Nissan, A., Koutsopoulos, H., 2011. Evaluation of the impact of advisory variable speed limits on motorway capacity and level of service. Procedia – Social Behav. Sci. 16, 100–109.
Noland, R.B., Quddus, M.A., 2006. Flow improvements and vehicle emissions: effects of trip generation and emission control technology. Transp. Res. Part D 11 (1), 1–14.
Papageorgiou, M., Kosmatopoulos, E., Papamichail, I., 2008. Effects of variable speed limits on motorway traffic flow. Transp. Res. Rec. 2047, 37–48.
Piao, J., McDonald, M., 2008. Safety impacts of variable speed limits – a simulation study. In: IEEE Conference on Intelligent Transportation Systems, Proceedings, ITSC. No. Proceedings of the 11th International IEEE Conference on Intelligent Transportation Systems, ITSC 2008. Transportation Research Group, School of Civil Engineering and the Environment. Southampton University, pp. 833–837.
Ranjitkar, P., Nakatsuji, T., Kawamua, A., 2005. Car-following models: an experiment based on benchmarking. J. Eastern Asia Soc. Transp. Stud. 6, 1582–1596.
Scora, G., Barth, M., 2006. Comprehensive Modal Emission Model (cmem), Version 3.01, User's Guide. Technical Report, University of California, Riverside, Center for Environmental Research and Technology.
Smulders, S., Helleman, D., 1998. Variable speed control: state-of-the-art and synthesis. 9th International Conference on Road Transport Information and Control, 454. Transport Research Center, pp. 155–159.
Stevanovic, A., Stevanovic, J., Zhang, K., Batterman, S., 2009. Optimizing traffic control to reduce fuel consumption and vehicular emissions: integrated approach with VISSIM, CMEM, and VISGAOST. Transp. Res. Rec. (2128), 105–113.
SUMO, 2013. Sumo homepage. Accessed 15th of October 2013. <http://sourceforge.net/apps/mediawiki/sumo>.
Torday, A., Casas, J., Aymami, J., Gerodimos, A., 2011. Evaluating the efficiency of variable speed policies using microsimulation. In: the 11th Asia-Pacific ITS Forum & Exibition, Kaohsiung, Taiwan.
Vallamsundar, S., Lin, J., 2011. Moves and mobile: a comparison of ghg and criteria pollutant emissions. In: TRB 90th Annual Meeting Compendium of Papers, Washington D.C., U.S.
van den Hoogen, E., Smulders, S., 1994. Control by variable speed signs. results of the dutch experiment. In: Seventh International Conference on Road Traffic Monitoring and Control. No. 391, Heidemij Advies, pp. 145–149.
van Toorenburg, J.A.C., de Kok, M.L., 1999. Automatic Incident Detection in the Motorway Control System mtm. Technical Report, Bureau Transpute, Gouda, Holland.
Yang, H., Jin, W.-L., 2014. A control theoretic formulation of green driving strategies based on inter-vehicle communications. Transp. Res. Part C: Emerg. Technol. 41 (0), 48–60.
Yelchuru, B., Adams, V., Hurley, E., Bonifera, V., 2011. Aeris: State of-the-Practice Scan of Environmental models. Technical Report, Research and Innovative Technology Administration (RITA), U.S. Department of Transportation, Washington DC, U.S.
Zhang, K., Batterman, S., Dion, F., 2011. Vehicle emissions in congestion: comparison of work zone, rush hour and free-flow conditions. Atmos. Environ. 45 (11), 1929–1939.