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Impacts of a Cooperative Variable Speed Limit System

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Abstract

Variable Speed Limit Systems (VSLS) where variable message signs show speed limits based on, for example,traffic volume or road conditions exists on motorwaysin many countries. The purpose of the VSLS is to decrease the number of accidents and to increase traffic efficiency. Cooperative systems are a type of intelligent transport system that has received increasing interest lately. The central part of a cooperative system is communication between vehicles and/or vehicles and the infrastructure. In this paper, a cooperative systems extension of a VSLS is proposed and evaluated by means of traffic simulation. By adding cooperative systems functionality to an existing VSLS there is a potential for further increase in traffic efficiency and also to reduce the environmental impacts of the traffic on the road. In the proposed cooperative VSLS, communication between the vehicles and the infrastructure is made available via a roadside unit communicating the speed limits to vehicles upstream on the road. The results of the study show that the cooperative VSLS has a potential to contribute to flow harmonization and to reduce environmental impacts.

Keywords: cooperative systems; intelligent transport systems (ITS); variable speed limit systems (VSLS); traffic simulation; environmental impacts; traffic efficiency

1. Introduction

Traffic congestion on motorways is a common problem in many countries around the world. Increasing traffic flows are resulting in problems related to safety as well as efficiency. Another problem

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that is receiving more and more attention is the environmental impacts of road traffic congestion, such as pollutant and greenhouse gas emissions.

Much research have been focusing on trying to solve problems related to congestion on motorways by introduction of Intelligent Transport Systems (ITS) to control the traffic flow. One commonly used motorway control strategy is variable speed limit systems (VSLS), where variable speed limit signs are linked together via a decision algorithm often based on speed or flow. VSLS are often included in motorway control systems (MCS), together with functions like lane closure, warnings, etc. The purpose of VSLS is to make drivers more aware of the actual speed conditions on the road, hopefully leading 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 & Smulders, 1994)indicate benefits in terms of safety and efficiency.Harmonized traffic flows, more homogenous headways and decreased variance in speed are the most frequently observed benefits for the mentioned systems. The system implemented on the M25 in the UK (Highway Agency, 2007) has led to reductions in exhaust emissions by 2-8%, depending on type of emission and a reduction of around 15% in injury accidents.

Advancements in communication technology have opened up for the development of ITS that utilize vehicle-to-vehicle and/or vehicle-to-infrastructure communication, so called cooperative systems. The expectation of the industry as well as road authorities and research organizations, is that cooperative systems will improve safety, efficiency and reduce the environmental impacts of road traffic in an even more efficient way than the ITS that are in operation today.

In this paper, a cooperative systems extension of a VSLS is proposed. By using cooperative systems, i.e. vehicle-to-infrastructure communication, together with the information already available through an existing VSLS, a cooperative VSLS can be developed. When a cooperative VSLS is introduced, more detailed information about traffic conditions on the road can be given to the vehicles at an earlier stage. This may result in even more harmonized flows and therefore reduced environmental impacts of motorway traffic, compared to the effects of today's VSLS. We study impacts of the proposed cooperative VSLS using microscopic traffic simulation. By the use of microscopic traffic simulation individual vehicles in the traffic stream are considered, which allows modeling of a cooperative VSLS. The contribution of the paper is an estimation of the potential benefits of extending existing motorway VSLS by incorporation of cooperative systems technology. Effects of the cooperative VSLS on exhaust emissions and traffic efficiency are presented.

The remainder of the paper is organized as follows. In the next section, a literature review of existing studies of VSLS is presented. In the section 'A cooperative variable speed limit system' we introduce an approach for implementing the cooperative VSLS and an algorithm for calculating speed recommendations for the cooperative VSLS. An overview of the method used and the simulation tool used for evaluating the cooperative VSLS is then given. Computational results comparing the cooperative VSLS to an existing VSLSare presented in section 'Results'. Finally, conclusions from the study are given together with suggestions for further research in the area.

2. Literature review

Already implemented VSLS exists in many countries today with various functionalities depending on purpose, location, etc. They are often included in a MCS together with lane closure, and different type of warnings, like adverse weather warnings. Examples of implemented VSLS include the systems in the UK(Highway Agency, 2007) and the Netherlands (van den Hoogen & Smulders, 1994). Studies of these systems indicates benefits in terms of road safety and traffic efficiency,with harmonized traffic flows, more homogenous headways and decreasedvariance in speed as the most frequently observed benefits.

The system implementedon the M25 in the UK (Highways Agency, 2007) has resulted inreductions ofexhaust emissions by 2-8%, depending on type of emission and a reduction of around 15%in injury accidents.A state-of-the-art study on systems implemented in Germany, Netherlands andUK (Smulders & Helleman, 1998) shows results that are in line with the findings in the UK, with harmonized flows as the most highlighted benefit. No significantimprovements have been seen on congestion, throughput and capacity in this study. Both advisory and compulsory variable speed limits can be used in the VSLS. A study on the Swedish VSLS (Nissan & Koutsopoulos, 2011) indicates that the effects when using only advisory speed limits are very limited.

One way to evaluate VSLS is by the use of microscopic traffic simulation. Microscopic traffic simulation will 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 microscopic traffic simulation, resulting in good indications on the system performance.Most of the simulation studies have been focusing on safety, see e.g.Allaby et al. (2007)and efficiency, see e.g. Papageorgiou et al.(2008). Fewtraffic 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).

Allaby et al. (2007), Lee et al. (2006) and Abdel-Aty et al. (2006) focused on evaluating different control strategies for VSLS with respect to their effect on safety. Lee et al.(2006) showed that control strategies including accurate predicted speed on the road have greater effect than systems considering predefined speed limits. This shows the importance of having good strategies for choosing speed limits and also that the closer the speed limit is to the actual speed the better. Papageorgiou et al.(2008) also considered control strategies but with respect to their effect on traffic efficiency subject to preserve road safety and environmental impact.

Torday et al. (2011) and Juan et al. (2004) concluded that the benefits from the systems are largely dependent on the traffic volume. During congestion, the systems tend to have more impact. However, according to Juan et al. (2004), the VSLS are not well-working in very high volume conditions.

Hellinga and Mandelzys(2011) have investigated the effect of variations in the driver compliance of the VSLS. They concluded that safety is positively correlated with compliance and travel time is negatively correlated with compliance. This is in line with other studies showing that when designing control strategies one have to consider a trade-off between safety and travel time (see e.g. Allaby et al. (2007), Lee et al. (2006) and Juan et al. (2004)).

To our knowledge, not much research exists on cooperative VSLS, especially not with respect to the environmental impacts of the system. A related system is considered by Piao and McDonald(2008), who discuss the safety impacts of a VSLS combined with an in-vehicle application.

3. A cooperative variable speed limit system

The VSLS function included in Stockholm's MCS and the Dutch MCS is used as reference system for the proposed cooperative VSLS (see van Toorenburg and de Kok(1999)).The VSLS function consists of detectors measuring the current traffic conditions such as average velocity on the road, and variable message signs showing recommended or compulsory speed limits based on the traffic conditions. 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. The speed limits shown on signs upstream of the detection point are higher than the speed limit shown on the sign closest to the detection point to avoid large changes in speed limit from one road segment to the next.

When the existing VSLS is considered, the variable message signs are used for showing information to the drivers about the speed limits, and when a cooperative VSLS is considered, the variable message signs are used as roadside units sending out information to the vehicles about speed limits. The speed limits given to the vehicles are calculated based on how far away the vehicles are from the new speed limit, the current speed of the vehicle and the reference speed. As a result of this approach, when the vehicles reaches the new speed limits they have been given speed recommendations at predefined time intervals resulting in a smooth deceleration/acceleration towards the new speed limits. The speed limits for the VSLS and the cooperative VSLS are assumed to be compulsory.

For both the VSLS and the cooperative VSLS the maximum allowed speed on the road is assumed to be 120 km/h. The average velocities given at the detectors are calculated by the use of a smoothed harmonic average speed. A smoothing parameter of 0.25 is used to take into acount approxemately the 4 last vehicles. See van Toorenburg and de Kok (1999) for a more detailed description of the calculations of the smoothed harmonic average speed and the smoothing parameter used. If the average velocity 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 average velocity 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 average velocity at a detector where the variable speed sign is showing 60 km/h goes above a certain threshold, which is set to 55 km/h, the compulsory speed is updated to120 km/h. The speeds 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 (see e.g. Lind and Strömgren(2011)). It is assumed that the most restrictive lane is considered, i.e. the lane with the lowest average velocity is considered when calculating the speed limit for all lanes. The speed limits are updated every fourth second.

When implementing the VSLS it is assumed that all vehicles follow the given speed limits and the vehicles are able to read the speed limit signs within a range of 150 meters. Approaching vehicles are updating their maximum allowed speed when located within the given range.

For the cooperative VSLS, the speed limits calculated based on the smoothed harmonic average speed are used as reference speeds in order to be able to calculate speed recommendations that are given to the drivers at specific points in time. The vehicles receive updates of the speed limit signs via the roadside units during the whole road segment (i.e. 500 meters). The speed recommendations given to the vehicles are calculated based on the equations of motion. First the acceleration of the vehicles, to adapt to the given speed limit when located at a certain place on the road segment, is calculated. For a given vehicle, the next downstream roadside unit is considered.

$$a_{t,i} = \frac{v_{t,j}^2 - u_{t,i}^2}{2 \cdot s_{t,ij}} \tag{1}$$

where $v_{t,j}$ is the speed communicated from roadside unit j (located in front of vehicle i) at time t, $u_{t,j}$ is the speed of vehicle i at time t, $s_{t,ii}$ is the distance between vehicle i and roadside unit j (located in front of vehicle i) at time t and $a_{t,i}$ is the acceleration of vehicle i at time t needed to adapt to speed limit, $v_{t,j}$, when located at a certain place, $s_{t,ii}$, on the road segment.

The acceleration, see Eq. (1), is used to calculate a final recommended speed:

$$u_{t,i}^{rec} = u_{t,i} + a_{t,i} \cdot T$$

where $u_{t,j}$ is the speed of vehicle i at time t, $a_{t,i}$ is the acceleration calculated above, and T is the time until next update.

It is assumed that all vehicles receive the information sent out from the roadside units, regardless of their position within the road segment and that the given speed recommendations are obeyed.

When setting the time until next update of the speed it is important that the update interval is comfortable for the drivers and also that no big jumps in speed between two updates occur, resulting in unnecessary accelerations and decelerations. In this first experiment the time until next update is set to 1 second. This is a quite small interval which could affect the driver negatively since he/she is getting new speed limit recommendations quite often. The reason for doing this is to get a smooth increase/decrease of the speed without big jumps in the speed recommendations except from when a change in the VSLS occurs. Since the speed recommendations are frequently updated, the changes from one recommendation to the next is not that big and therefore it might not disturb the driver even though it is updated quite frequently.

4. Method

Earlier studies have showed that VSLS have a potential to improve traffic efficiency and there are also indications of reduced environmental impacts due to VSLS. Cooperative systems are expected to contribute with even bigger improvements in these areas. Implementation of cooperative systems in the traffic system will be associated with substantial investmentsdue to the technology needed. The need for a large coverage area is essential for the system to work well, both with respect to the number of equipped vehicles and the number of roadside stations/units. Therefore, there is a need of evaluations of the systems before they are implemented. Microscopic traffic simulation is a good alternative for such a priori evaluations.Microscopic traffic simulations consider individual vehicles in the traffic stream, which is necessary to allow modeling of cooperative systems. A microscopic traffic simulation modeling approach will therefore be suitable for evaluating the cooperative VSLS.

The open source microscopic traffic simulation tool Simulation of Urban Mobility, SUMO, (Krajzewicz, 2010; SUMO homepage, 2011) is used to model the VSLS and the cooperative VSLS. It is a microscopic traffic simulation tool developed in order to handle large networks with fast execution times. The current version of the model is a multi-modal, space continuous and time discrete model. SUMO has been continuously developed since 2000 and several projects have used SUMO over the years, see e.g. iTetris(2010) and DRIVE C2X (2011).

In SUMO the default car-following model used is a space continuous, time discrete model based on Gipps car-following model developed and described by Krauß(1998). The current lane-changing model in SUMO consider necessary gaps to preceding vehicles based on a highway or in an urban environment and the benefit of changing to a different lane. To evaluate the environmental effects of the simulated traffic in SUMO, the HBEFA (2011) (Handbook Emission Factors for Road Transport) emission factors are applied.

The VSLS implemented in SUMO is a simplified version of the systems that exists on the E4 in Stockholm. The cooperative VSLS is implemented based on the same assumptions as the existing VSLS, such as calculations of average velocity, location of roadside units, etc., together with additional assumption taking into account the functionalities related to the cooperative part. A traffic control interface (TraCI) is used to get access to SUMO during the simulation and a python script is used to communicate with SUMO and for implementation of the VSLS and the cooperative VSLS. The new maximum allowed speed given in the VSLS and the cooperative VSLS, needed for calculating the desired speed in the car following model, is communicated to SUMO via the TraCI. See Fig. 1for an illustration of the structure.

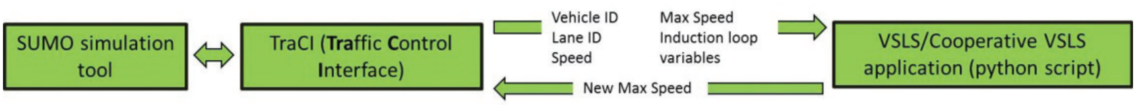

Fig. 1. Illustration of SUMO's Traffic Control Interface (TraCI)

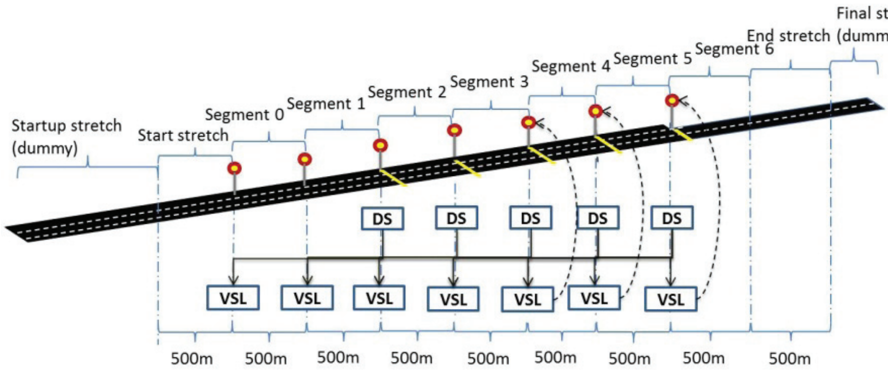

Fig. 2. Illustration of the considered VSLS and cooperative VSLS (VSL:Variable Speed Limit, DS:Detector System)

An open traffic system consisting of one stretch of motorway, without on- or off-ramps, is used to simulate the VSLS and the cooperative VSLS. The reason for choosing this elementary design is to be able to easily evaluate the effects cooperative systems technology will have on an existing VSLS. The simulated road is divided into 500m segments, with one detector and one variable message sign per lane on each segment. For the three last segments, the road is narrowed down from three lanes to two lanes resulting in a bottleneck. The reason for this is to be able to evaluate the effects of flows beyond the capacity of the bottleneck and where the VSLS is activated. See Fig. 2 for an illustration of the considered VSLS and cooperative VSLS.

The simulation is performed during a half-an-hour interval. The flow is low during the first 10 minutes, 1200 vehicles per hour (around 20% of the capacity of a road with three lanes), resulting in free flow speed during this time interval. After 10 minutes the flow is increasing to 3900 vehicles per hour (around 70% of the capacity of a road with three lanes), causing congestion on the segments upstream of the bottleneck. The last 10 minutes the flow is reduced to 1200 vehicles per hour again. This gives a picture of how the two systems behave during congested conditions and a comparison between the two systems can be made.

The vehicle parameters used in the simulation are set to standard values used in SUMO version 0.13.1 (see SUMO homepage (2011) for a detailed documentation of the parameters used). The randomness of the simulations performed is taken under consideration by performing 10 replications of the simulation for both the VSLS and the cooperative VSLS and besides looking at the mean also consider the standard deviation of the replications. The standard output generated from SUMO is used to evaluate speed, travel time and exhaust emissions. Acceleration and deceleration output is based on raw data collected from SUMO during the simulation by use of the TraCI.

5. Results

Effects of the VSLS and the cooperative VSLS related to traffic efficiency and environmental impacts are presented in the paper. Evaluation of the environmental impacts is done by analyzing effects on fuel consumption, CO and CO2, and evaluation of traffic efficiency is done by analyzing the effects on speed, travel time and acceleration/deceleration trajectories.

To identify different traffic behaviors when comparing VSLS and the cooperative VSLS a time-space diagram showing the vehicle trajectories from a selected replication is investigated. Fig. 3 shows that the patterns for the VSLS and the cooperative VSLS are different. Similar patterns can be seen from all the replications performed.

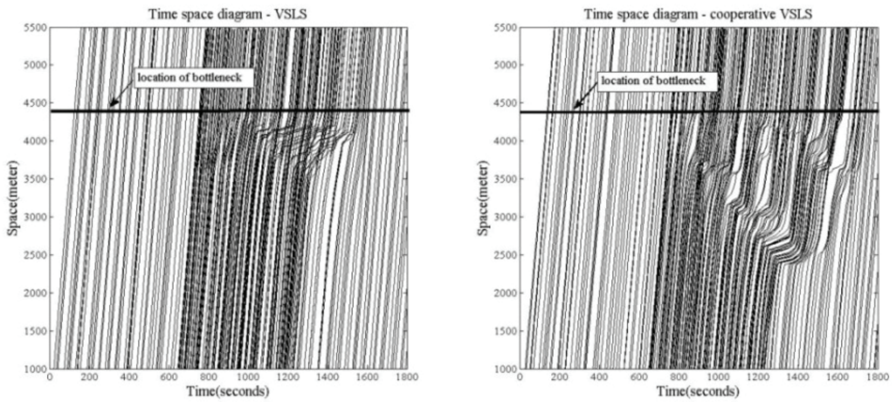

Fig. 3. Time-space diagram for the VSLS and the cooperative VSLS showing the trajectories for every fifth vehicle in the system (1 sec in update time for the cooperative VSLS)

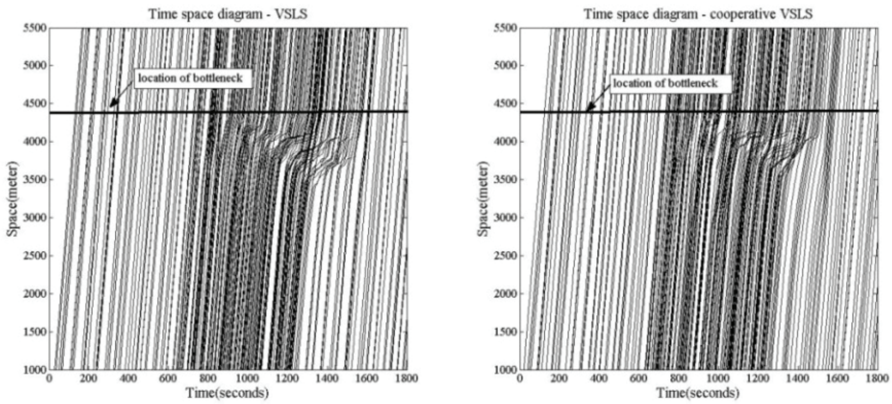

Fig. 4. Time-space diagram for the VSLS and the cooperative VSLS showing the trajectories for every fifth vehicle in the system (4 sec in update time for the cooperative VSLS)

The VSLS result in a slow moving queue at the bottleneck. The vehicles in the queue are almost at standstill after around 1000 seconds. In the case of the cooperative VSLS, the queue is moving away from the bottleneck due to the fact that the vehicles start to slow down already at a distance of 500 meters from the roadside unit in front of them and below that. One can also see that a new queue starts to form at the bottleneck after some additional time with high flow. The reason for this is because the queue is moving backwards, resulting in an update in the speed recommendations to 120 km/h again, since the average velocity is higher than the threshold after some time. The vehicles downstream the queue accelerates to the new speed recommendations, causing the new queue due to a flow beyond capacity level. The speed of the vehicles is smoothed out in the cooperative VSLS case and not as many vehicles seem to be in a standstill or almost standstill mode. This result appears since the vehicles get updates of the speed limit and adapt their speeds to the speed limits every second. If the time between two updates is longer, the result becomes closer to the VSLS case (Fig. 4). This indicates that the effects of the cooperative VSLS is higher the more frequent the updates. Although, it could be argued that update times of 1 second are unrealistic, since the drivers will have trouble reacting on such frequent changes in speed limit. The user acceptance aspects could also be discussed since the driver would probably be disturbed or not prefer to have updates of the speed every 1 second. Even so, the mean velocity used by the system is dependent of approximately the last 4 passing vehicles and the speed limits is only updated every fourth second, therefore the speed limits sent out from the roadside units are not changed within 1 second intervals. This will result in that the speed limits between two updates in most cases are close to each other and the driver will not be presented with big jumps in the speed limit recommendations.

Comparison of the acceleration/deceleration distributions is one way to measure the effectiveness of the systems. High values of acceleration/deceleration indicates hard acceleration and hard braking (deceleration), resulting in higher fuel consumption and excess exhaust emissions.

Fig. 5 shows the frequencies of different acceleration/deceleration rates in percentage for all segments of the simulated road.

The cooperative VSLS result in higher frequencies of acceleration and deceleration rates close to zero compared to the VSLS, while for the VSLS higher acceleration and deceleration rates are more frequent than for the cooperative VSLS. The larger amount of very high decelerations for the VSLS indicates more frequent hard braking. Moreover, the higher amount of accelerations between 1.5-3.5 m/s^2 and above for the VSLS indicates that the vehicles in the cooperative VSLS case have a smoother acceleration and deceleration pattern than the vehicles in the VSLS case.

The larger amount of high acceleration and deceleration rates for the VSLS case indicate more frequent harder braking and sudden speeding up, which most probably will result in higher exhaust emissions and fuel consumption. The HBEFA-based emissions and fuel consumption calculated in SUMO gives an indication of if this is the case or not. In Table 1 it can be seen that the cooperative VSLS result in lower CO and CO_2 emissions and lower fuel consumption than the VSLS. Even though the change is not that big (around 1.5-2.5% depending on type of emission/fuel consumption) the confidence intervals does not overlap, showing that the values are significantly different for the exhaust emissions and the fuel consumption presented.

The mean speed on the road segments have been measured over 30 second intervals. The results from the cooperative VSLS and the VSLS shows that the mean speed for the cooperative VSLS are a little bit below the mean speed for the VSLS for most of the segments.

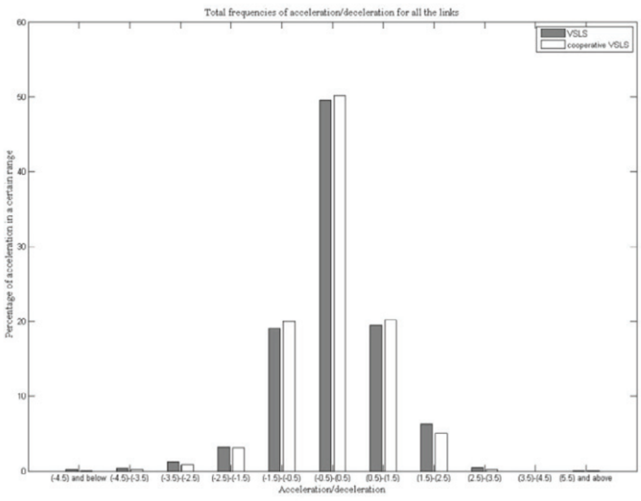

Fig. 5. Total frequencies of accelerations/decelerations rates (in percentage) of all links in the system for the VSLS and the cooperative VSLS

Table 1. CO, CO_2 and fuel consumption for the VSLS and the cooperative VSLS

	VSLS	cooperative VSLS	Difference	Difference in percentage
Total amount of CO(kg) during the simulation period	33.82	32.92	0.90	2.66%
Confidence interval	[33.70, 33.93]	[32.77, 33.07]		
Total amount of CO_2(kg) during the simulation period	1754.68	1728.09	26.59	1.52%
Confidence interval	[1750.49, 1758.87]	[1723.46, 1732.73]		
Total amount of fuel consumption (l) during the simulation period	699.57	688.97	10.60	1.52%
Confidence interval	[697.90, 701.24]	[687.12, 690.81]		

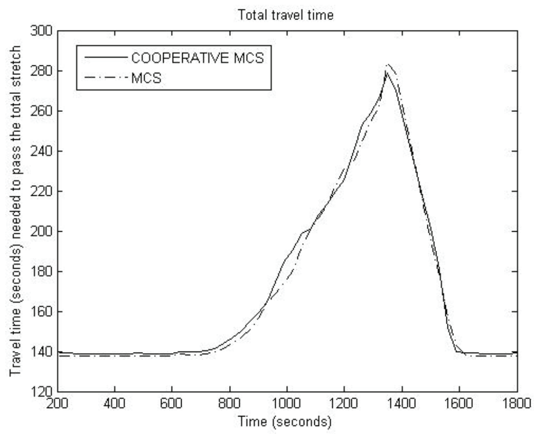

Fig. 6. Total mean travel time over the whole stretch based on 30 seconds intervals.

Lower mean speed on the segments for the cooperative VSLS could cause longer travel times, but it could also indicate that the vehicles in the VSLS case have a less harmonized driving style, with a more varying speed pattern. When looking at the travel time over the whole stretch (Fig. 6), there are no big differences between the VSLS and the cooperative VSLS. This will most probably be a result of a more varying speed pattern (less harmonized flow) in the VSLS case. This is also confirmed by the fact that higher acceleration and deceleration rates appears more frequently in the VSLS case.

6. Conclusions

In this paper we have introduced a cooperative systems extension to an existing VSLS. The proposed cooperative VSLS was evaluated by comparing it to an existing VSLS by means of traffic simulation. The cooperative systems extension is developed using the equations of motion. The algorithm used for deciding new speed limits, both for the VSLS and the cooperative VSLS, is based on the existing VSLS included in the MCS in Stockholm. When introducing a cooperative VSLS the vehicles will receive information about the updated speed limits from the VSLS before reaching a point where they can actually read the speed limit signs. The speed recommendations is given to the vehicles at predefined points in time and are depending on the speed of the vehicles, the speed limits given from the roadside unit located in front of the vehicles and the distance between the vehicles and the roadside unit.

The simulation results show that the cooperative VSLS gives rise to different queue formation than the

VSLS. In the cooperative VSLS case, the vehicles adapt their speed earlier and continuously, resulting in a queue moving upstream from the bottleneck, while in the VSLS case the queue is stationary and growing upstream from the bottleneck. The cooperative VSLS has been shown to reduce the very high acceleration and deceleration rates compared to the existing VSLS. This indicates that the flow is more harmonized for the cooperative VSLS, with a less varying speed pattern for the vehicles compared to the VSLS. The higher acceleration and deceleration rates for the VSLS suggest higher fuel consumption and more exhaust emissions. The simulation based emission estimation shows that the fuel consumption, as well as the CO and CO_2 emissions is lowered by approximately 1.5-2.5% for the cooperative VSLS compared to the VSLS. The mean speed in the cooperative VSLS case is lower than the mean speed in the VSLS case for most of the road segments, and especially during the congested period. However, the lower mean speed does not seem to have a negative impact on the travel time. This indicates more stable speed patterns for the cooperative VSLS compared to the VSLS. The conclusion is therefore that, this study shows the potential of using a cooperative VSLS to increase traffic efficiency by harmonizing traffic flows and thereby reducing exhaust emissions and fuel consumption.

The study presented is a first study included in a greater project with the aim to study cooperative systems that can contribute to improved traffic efficiency and decreased environmental impacts. The results show the need for further investigations of systems like the cooperative VSLS presented here and related cooperative systems. A possible extension of the study presented in this paper could be to include more advanced functions and/or additional cooperative systems working together with the VSLS, such as cooperative lane changing and cooperative adaptive cruise control. Such systems might result in even greater impacts on traffic efficiency and environment than the ones that were observed here.Drivers' behavior is an important aspect that has not been considered in this study. For example the time until next update for the cooperative VSLS is in this study set to 1 second. An alternative could be to update the recommended speed only when the difference between the new speed and the vehicle's speed is above a certain threshold. This would probably result in less updates and a more realistic and user-friendly communication application inside the vehicle. Another aspect could be to let the in-vehicle part of VSLS communicate with the roadside units and adapt the speed to the speed recommendations without interaction with the driver. Also drivers' reaction and how well they respond to a cooperative VSLS could be investigated and implemented to simulate more realistic behavior. Depending on the distance to the roadside unit the probability of actually receive information about the speed limit recommendations will probably be different. This could be taken into account by the use of a probability distribution, where the probability of receiving the information is dependent on the distance between the vehicle and the roadside unit. A quite simple road has been investigated and the effects from on-and off ramps have not been considered at all. This will most probably have effect both on the VSLS and the cooperative VSLS, with more diversified speeds as a result of the speeds of the vehicles entering the main road. Evaluations of effects from such extensions are important since this is a more probable scenario in the real world. The aim with this study has not been to find the weaknesses and limitations in the existing VSLS, but to show on the potential of adding a cooperative part to an already existing VSLS and the results are found as useful for further investigation of the cooperative VSLS. One limitation with the existing VSLS is that the methods for calculating the speed limits are based on quite simple calculations. Different control strategies for the VSLS can be considered, that responds better to the actual conditions on the road. In this case it will be important to take into account that control strategies focusing on improved efficiency, might give a decrease in safety.

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Reference

Abdel-Aty, M., Dilmore, J., Dhindsa, A. (2006). Evaluation of variable speed limits for real-time freeway safety improvement. *Accident Analysis & Prevention*, Vol. 38, No. 2, pp. 335-345.

Allaby, P., Hellinga, B., Bullock, M. (2007). Variable Speed Limits: Safety and Operational Impacts of a Candidate Control Strategy for Freeway Applications. *Intelligent Transportation Systems*, IEEE Transactionson, Vol. 8, No. 4, pp. 671-680.

DRIVE C2X. (2011). *DRIVE C2X-Accelerate cooperative mobility* Retrieved Dec., 2011, from http://www.drive-c2x.eu/project.

HEBFA. (2011). *The Handbook Emission Factors for Road Transport* Retrieved Dec., 2011, from http://www.hbefa.net.

Hellinga, B., & Mandelzys, M. (2011). Impact of Driver Compliance on the Safety and Operational Impacts of Freeway Variable Speed Limit Systems. *Journal of Transportation Engineering*, Vol. 137, No. 4, pp. 260-268.

Highway Agency. (2007). M25, Controlled Motorway, Summary report. http://www.highways.gov.uk
iTetris. (2010). iTETRIS: *The Integrated Wireless and Traffic Simulation Platform for Real-Time Road Traffic Management Solutions* Retrieved Dec., 2011, from http://www.ict-itetris.eu.

Juan, Z., Zhang, X., Yao, H. (2004, 3-6 Oct. 2004). Simulation research and implemented effect analysis of variable speed limits on freeway. Paper presented at the *Intelligent Transportation Systems*, 2004. Proceedings. The 7th International IEEE Conference on.

Krajzewicz, D. (2010). Traffic Simulation with SUMO - Simulation of Urban Mobility. In J. Barceló (Ed.), *Fundamentals of Traffic Simulation*, Vol. 145, pp. 269-293, New York Dordrecht Heidelberg London: Springer.

Krauß, S. (1998). *Microscopic Modeling of Traffic Flow: Investigation of Collision Free Vehicle Dynamics*. PhD, Köln University, Germany.

Lee, C., Hellinga, B., Saccomanno, F. (2006). Evaluation of variable speed limits to improve traffic safety. *Transportation Research Part C: Emerging Technologies*, Vol. 14, No. 3, pp. 213-228.

Lind, G., Strömgren, P. (2011). *Säkerhetseffekter av trafikledning och ITS*, Litteraturinventering, v0.9: Movea, Sweden.

Nissan, A., Koutsopoulos, H. N. (2011). Evaluation of the Impact of Advisory Variable Speed Limits on Motorway Capacity and Level of Service. *Procedia - Social and Behavioral Sciences*, Vol. 16, pp. 100-109.

Papageorgiou, M., Kosmatopoulos, E., & Papamichai, I. (2008). Effects of Variable Speed Limits on Motorway Traffic Flow. *Transportation Research Record*, 2047/2008, pp. 37-48.

Piao, J., McDonald, M. (2008, 12-15 Oct. 2008). Safety Impacts of Variable Speed Limits - A Simulation Study. Paper presented at the Intelligent Transportation Systems, 2008. ITSC 2008. 11*th International*

IEEE Conference on, Bejing China.

Smulders, S. A., Helleman, D. E. (1998, 21-23 April 1998). Variable speed control: state-of-the-art and synthesis. Paper presented at the Road Transport Information and Control, 1998. 9th *International Conference on* (Conf. Publ. No. 454).

SUMO homepage. (2011) Retrieved Dec., 2011, from http://sourceforge.net/apps/mediawiki/sumo

Torday, A., Casas, J., Aymami, J. M., Gerodimos, A. (2011). Evaluating the efficiency of variable speed policies using microsimulation. Paper presented at the The 11*th Asia-Pacific ITS Forum & Exibition*, Kaohsiung, Taiwan.

van den Hoogen, E., Smulders, S. (1994, 26-28 Apr 1994). Control by variable speed signs: results of the Dutch experiment. Paper presented at the Road Traffic Monitoring and Control, 1994., *Seventh International Conference on*, London, UK.

van Toorenburg, J. A. C., de Kok, M. L. (1999). *Automatic Incident Detection in the Motorway Control System MTM* Retrieved June, 2011, from http://www.durbit.se/Archives/ExternalPDF/Deliverables/PhaseIII/Domain3/P3D_A32.3_AID%20in%20the%20MCS%20system.pdf.