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SHORT REVIEW OF APPROACHES FOR VARIABLE SPEED LIMIT CONTROL

ABSTRACT

Urban motorways serve the traffic demand from adjacent dense populated urban regions and transit traffic. Combinations of these two traffic demand types generate periodically traffic congestions during the peak hours. The capacity drop effect is the most common cause of congestions. It occurs when the current traffic flow reached its maximal capacity of the observed urban motorway section. In order to alleviate the capacity drop effect and enable better level of service on motorways new traffic control methods are introduced. One of the used traffic control methods is variable speed limit control (VSLC). VSLC conducts homogenization and reduction of vehicle speeds what consequently decreases time needed to create a critical shockwave, which will induce the capacity drop. This paper presents a short overview of the latest VSLC algorithms originally designed for mitigation of traffic congestions and their effects on the motorway mainline. Firstly, simple reactive VSLC algorithms are introduced. Then approaches based on model based optimization are described. Possible coordination between VSLC and other motorway management strategies is also described in this paper.

KEY WORDS

Variable speed limit control, coordination, traffic control, fundamental diagram, motorways

1. INTRODUCTION

Originally, motorways are designed to provide larger maximal traffic capacity, which consequentially enables their higher Level of Service (LoS), compared to other types of roads. LoS is defined as a group of qualitative measures, which characterize operational conditions within the traffic flow and their perception by motorists and drivers [1]. Even though motorways are designed to serve higher traffic load in some cases they can be overloaded. Such situation is known under the term congestion. It is characterized by low speed and high traffic density what consequently reduces the motorway LoS. Congestions on motorways are most common on motorways with a larger number of adjacent on- and off-ramps. If those ramps are connected with a nearby dense urban area, they can be generators of high traffic demand for the motorway mainline capacity. Traffic demand originating from the urban area combined with transit traffic, which is also commonly served by motorways, can create good predispositions for congestion built up. If the spatial and temporal synchronisation between different types of traffic demands on motorways occurs, and if they are all intense enough, congestion will start. Place on motorway where congestion starts is usually known under the term bottleneck. In shockwave theory within moving congestions, this place is called “head of the shockwave“. Static congestions are usually present near on-ramps or near places of traffic incidents.

One of the control strategies used for congestion mitigation on motorways is variable speed limit control (VSLC). VSLC systems display speed limit information on appropriate variable message signs (VMSs). Therefore, speed limit values can be set according to the current traffic unlike fixed speed limit values. VSLC is a system that was first introduced in Germany more than three decades ago. Two main approaches can be found for VSLC implementation aiming at flow improvement. The first emphasizes the homogenization effect while the second approach is focused on preventing traffic breakdown or resolving existing jams by reducing the flow by means of speed limits [3]. Homogenization of vehicle speed reduces the speed difference between vehicles and consequently induces much stable and safer traffic flow. Mean speed of vehicles is reduced under the values that can cause occurrence of critical traffic density and consequently traffic congestion [2]. Flow reduction approaches focus more on preventing or resolving too large densities (including jams) by limiting the inflow to bottleneck places [3]. This paper presents a short overview of several commonly used and researched VSLC control strategies oriented on the flow reduction approach.

This paper is organized as follows. Section 2 describes the influence of VSLC on motorway traffic. In section 3 commonly used VSLC reactive controllers are presented. Section 4 presents VSLC approaches implemented using model based optimization. In section 5 an overview of possible coordination between VSLC and several other motorway management strategies is given. Paper ends with a conclusion section.

2. INFLUENCE OF VSLC ON MOTORWAY TRAFFIC

Because of the traffic’s nature, traffic jams are present even when the current traffic flow is below the maximum flow value. There are three types of traffic jams and they can be characterized as follows. First type is congested flow characterized by strong interactions between the vehicle-driver elements and nonlinear dynamic phenomena like jams and stop-and-go waves [4]. Second type is the classic traffic jam where in the first case speed approaches zero and density increases to its maximal or above the maximal value. In the second case, there are stop-and-go situations in which the flow, density and speed vary considerably. Third type of congested traffic is given by standing waves in which the flow along a motorway section is almost constant, but still the speed and the density changes considerably [4]. Main impact of VSLC, which aims to improve the performance of traffic flow, is deemed to be [2, 5]:

- Reduction of the mean speed at under critical densities;
- Homogenization of speeds, that is, reduction of speed differences among vehicles and of mean speed differences among lanes.

This means that VSLC can stabilize and homogenize the traffic flow thus reducing traffic jams, air pollution and road noise, and minimize the number of accidents. When applied, VSLC changes the fundamental diagram of the corresponding motorway section. The changes of the slopes in the fundamental diagram with variable speed limits (VSL) and without VSL applied can be seen in Fig. 1.

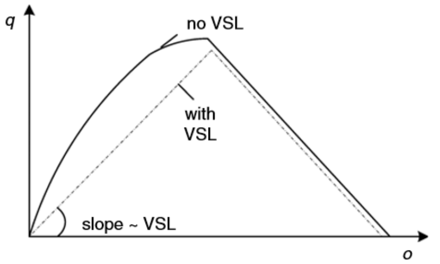

Figure 1 - Slope for traffic flow diagram without VSL and with VSL [2]

As mentioned before, one of the targeted impacts of VSLCs is enhanced traffic safety. When motorway stretches are selected for installation of VSLC, one of the main indicators of selection should be the frequency of registered accidents. Positive impact, which VSLC has on traffic safety, is a result of speed reduction and speed homogenization. Thus, the probability of accidents is reduced. Evaluations done on motorways with VSLC show a positive impact on traffic safety. Reduction in accident numbers can reach up to 30% [5].

Studies made in Finland showed that motorways with VSLC, even though it was firstly used to improve the fluency of the traffic flow, have increased traffic security in cases of bad weather conditions [5]. The positive effects are based first, on the efficient recognition of hazardous weather and road conditions, second, on the use of variable slippery road signs to support the VSLC system, and third, on the moderate use of the highest speed limit. In Finland, speed limits are lowered during winter time on most two-lane roads, but with VSLC it is possible to show higher speed limits under good conditions than it is with fixed signs.

3. SIMPLE REACTIVE CONTROLLERS

VSLC can be divided in two implementations groups. First group of implementations changes the speed limits based upon the decision of motorway operational staff. This type of VSLC implementations is mainly used in case of safety hazards such as traffic incidents, dense fog, wet road surface, etc. and it is not in the scope of this paper. Second group involves reactive VSLC controllers, which change the speed limit upon sensed traffic situation on the controlled motorway section. Based on the sensed data, the VSLC algorithm computes adequate speed limits. This type of VSLC implementations is mainly used in order to improve traffic flow characteristics. Simple reactive controllers are based on the classical negative feedback loop control framework. In continuation, reactive controllers for VSLC are described. First two are based on the fundamental flow-density relationship mapped to speed values given in Fig. 3 [6] and third one uses fuzzy logic rules to compute the speed limit value.

3.1 Mainline virtual metering

The mainline virtual metering approach is based on the concept of ramp metering [9]. Ramp metering reduces congestion on the motorway by limiting the inflow coming from an on-ramp. One of the often used ramp metering approaches is ALINEA. It is a local ramp metering approach, easy to implement and based on a pure integral control action represented as [9]:

$$R(kT_1) = R\big((k-1)T_1\big) + K_r[O_d - O(kT_1)], \tag{1}$$

where k is the time step, $R(kT_1)$ is ramp flow command, $R\big((k-1)T_1\big)$ is the ramp metering command at the previous cycle, K_r is a control parameter, $O(kT_1)$ is the measured downstream occupancy at the current cycle, and O_d is the desired value for the downstream occupancy that is typically chosen close to the critical occupancy O_c. This ramp metering approach can be generalized to a simple speed limit control algorithm based on the fundamental flow-density relationship. For this generalization the section i of the controlled motorway is regarded as a virtual on-ramp of section $i+1$ as shown in Fig. 2.

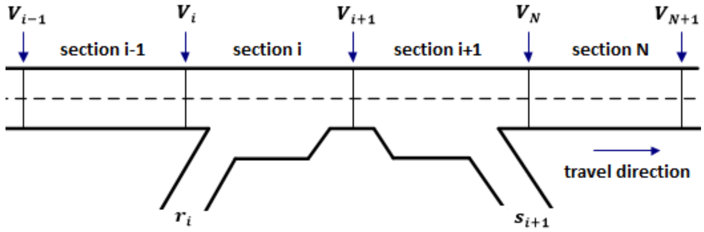

Figure 2 - Illustration of a uni-directional motorway stretch divided into N sections

The same integral control strategy as in the case of ramp metering is applied to regulate the metered flow rate Q_i from section i to section $i+1$. Equations that represent the flow rate Q_i are determined on inequalities below:

$$Q_i(kT_1) = \begin{cases} Q_{max} \text{ , } if\ \bar{Q}_i(kT_1) \geq Q_{max} \\ Q_{min} \text{ , } if\ \bar{Q}_i(kT_1) \leq Q_{min} \\ \bar{Q}_i(kT_1) \text{ , } otherwise \end{cases} . \tag{2}$$

Equation (3) provides the regulation of the flow at a particular section of the motorway, where k_v is a controller parameter, ρ_i is the density of the particular motorway section and ρ_d is desired density.

$$\bar{Q}_i(kT_1) = Q_i\big((k-1)T_1\big) + k_v \sum_{m=1}^{N_c} [\rho_d - \rho_{i+1}((k-1)N_cT_0 + mT_0] \tag{3}$$

The flow rate control described by equations (2) and (3) cannot be implemented as in the case of ramp metering, because in this case the control variable is the speed limit. Therefore, in order to regulate the traffic speed instead of the traffic flow rate, the flow command has to be mapped into a speed limit command using the flow-speed relationship shown in Fig. 3. The speed of the traffic flow in each section i has to be bounded as follows:

$$V_{min} \leq V_i(kT_i) \leq V_{max}, \tag{4}$$

where V_{max} is the maximum speed limit allowed (often set to be the default speed limit), and V_{min} is the lowest speed limit we want to apply. Hence, Q_{min} is set as the flow corresponding to V_{min}, and Q_{max} is the flow corresponding to the critical density (capacity flow). The capacity flow is usually not achieved at the maximal allowed speed [6, 7, 9].

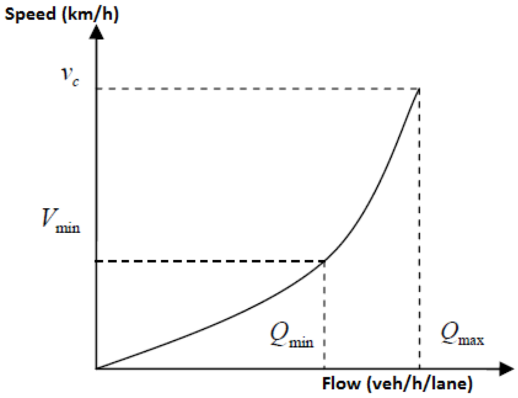

Figure 3 - Strictly increasing function f(Q) from [Qmin,Qmax] to [Vmin,Vc] [6]

The mapping $f(Q)$ is based on the estimated flow-density relationship that is assumed to be:

$$q = \rho V_f \exp\left[-\frac{1}{\alpha}\left(\frac{\rho}{\rho_c}\right)^{\alpha}\right], \tag{5}$$

where V_f is the free flow speed, ρ_c is the critical density, and the exponent α is estimated online or offline using real traffic data. When C_i (control variable of each controlled motorway section) is inactive, the desired speed limit is the default speed limit of the i^{th} freeway section. If C_i is active, section i requires calculation of a new speed limit. The new value of the speed limit can be determined by the function:

$$\bar{V}_i(kT_i) = f(Q_i(kT_i))\ . \tag{6}$$

However, $\bar{V}_i$ generated by (6) may lead to unsafe changes of speed limits. For practical purposes, the following speed limit V_i is used:

$$V_i(kT_1) = \begin{cases} V_i\big((k-1)T_1\big) - C_v\ , & if\ \bar{V}_i(kT_1) \leq V_i\big((k-1)T_1\big) - C_v \\ V_{i+1}(kT_1) + C_v\ , & if\ \bar{V}_i(kT_1) \geq V_{i+1}(kT_1) + C_v \\ \bar{V}_i(kT_1)\ , & otherwise \end{cases}, \tag{7}$$

where C_v is a positive constant which represent the maximal allowed change of the speed limit (usually $10[\frac{km}{h}]$) and $\bar{V}_i(kT_1)$ is the current space mean speed of traffic flow in section i [6].

3.2 Proportional speed controller

The proportional speed limit controller was developed to further simplify the mainline virtual metering speed controller described above. Ramp metering is usually active when the mainline traffic volume is high. Accordingly, the fixed chosen desired occupancy makes sense. Moreover, the dynamic variable speed limit is only necessary when a disturbance happens, such as an accident or a wave with increased traffic density. The desired density in such a situation is usually difficult to predict, because of adduced problems such as traffic volume (capacity drop), and freeway geometry [7]. For this reason it is advisable to have a speed controller that appropriately responses to the changes in downstream density instead of a fixed desired density.

Assume there is a motorway segment divided into *N* sections, as shown in Fig. 2 and a disturbance happened in the most downstream section *N*. The speed controller of sections that are upstream of section N would be active and response to their downstream density changes [8]. Therefore, the speed controller makes decisions based on activities of the control variable C_i and calculates the new speed limit value [6]. Aggregated traffic state variables are collected from traffic surveillance systems. The traffic state variables can be also estimated. The controller generates command signals every T_1 seconds, where $T_1 = N_c T_0$, T_0 is discretization time and N_c is a positive design integer. Let I_v signify the set of road section indices in which speed limits are controlled. Let C_i denote a control variable of each section $(i \in I_v)$. The controller generates the desired speed limit $\bar{V}_i$ for section i as presented in Fig. 3. To determine when C_i is active or not, density in the following section ρ_{i+1} for the particular moment nT_1 has to be measured. The following decisions observe three cases:

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

The speed of the traffic flow in each motorway section i is bounded with (4). As already mentioned, if C_i is inactive the speed limit in each section remains identical to the default speed limit. Active state of C_i requires calculation of the new speed limit value. In that case, equation (7) is used to determine the new speed limit value. If C_i is inactive at time $(k-1)T_1$ and becomes active at time T_1, the speed limit is given as:

$$V_i(kT_1) = \begin{cases} V_{i+1}(kT_1) + C_v\,, & if\ \bar{V}_i(kT_1) \geq V_{i+1}(kT_1) + C_v \\ \bar{V}_i(kT_1) = f\big(\rho_{i+1}(kT_1)v_{i+1}(knT_1)\big)\,, & otherwhise \end{cases}. \tag{9}$$

By using the fundamental equation of traffic flow $Q = \rho v$, $f\big(\rho_{i+1}(kT_1)v_{i+1}(kT_1)\big)$ in (9) can be expressed as a function of $f(Q)$. Then $\bar{V}_i(kT_1)$ can be determined with the relationship $V = f(Q)$ shown in Fig. 3 [6].

3.3 Fuzzy logic based controllers

Rule-based algorithms are widely used in VSLC applications because of their comprehensibility and ease of application [23]. In rule-based algorithms, speed limits are determined based on some pre-specified rules. Main problem is that the most algorithms proposed in the literature under this category are rather rough for speed control. Rough nature of these algorithms is induced by using crisp sets bases on which control rules are created. Crisp sets cannot adequately present traffic situations due to the non-linear and non-stationary nature of traffic flows. Fuzzy logic-based VSLC uses fuzzy sets, which conducts separation of attribute domains into several overlapping intervals. The discretization using fuzzy sets can help to overcome the sensitivity problem caused by crisp discretization used in the existing VSLC algorithms [23].

Whole VSLC control system is designed in the form of a fuzzy inference system. This type of control system is based upon three major steps. In the first step, crisp input values are accepted and converted into a set of fuzzy variables defined by membership functions. Second step is named inference engine. It evaluates all rules in parallel based on the fuzzy set theory that describes the interpretation of the logical operations. Output of this step is a combination of inference results of these rules through the aggregation process. Final step conducts defuzzification of the aggregation product into a crisp output. In Fig. 5 schematic example of a fuzzy inference system for VSLC proposed in [23] is presented.

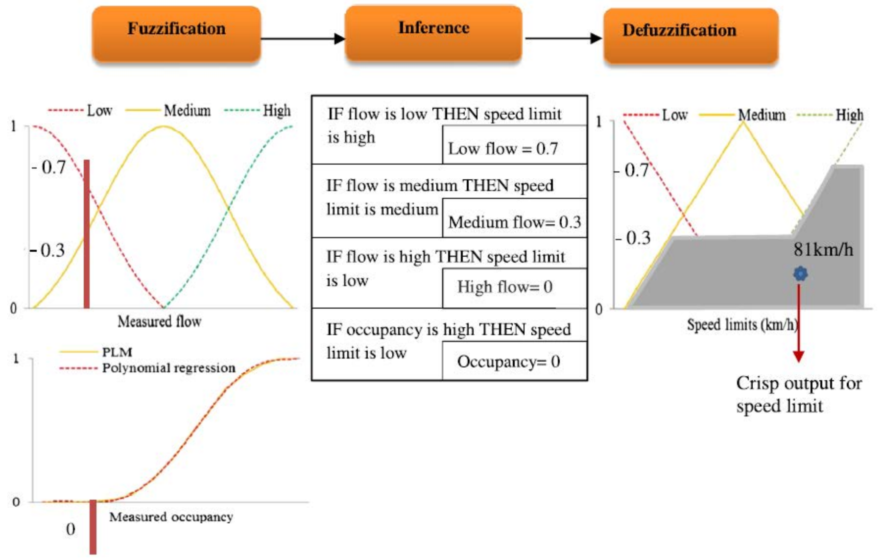

Figure 5 - Schematic example of fuzzy inference system for VSLC proposed in [23]

4. MODEL BASED OPTIMIZATION

VSLC algorithms created using model based optimization are also reactive but they control law is more complex. Currently they represent the most advanced approach for mitigation of congestions on motorways using VLSC. Model-based optimization methods construct a regression model that predicts performance of the controlled system and then use this model for optimization. Mentioned type of optimization is often used for very complex dynamical systems. Accurate modelling of such systems is connected with significant challenges. Example of such a system is the motorway traffic system with its numerous entities (vehicles) and their complex interactions (driver behaviours) in traffic flows.

Often used model based optimization in VSLC is model predictive control (MPC). The main advantage of MPC is the fact that it enables optimization of the control action in the current time step, while taking information about future time steps into account [10]. This is achieved by optimizing a finite time-horizon, but only implementing the obtained optimized control action into the current time step. In another words, MPC has the ability to anticipate future events and can take control actions accordingly. Additionally, MPC based controller has the ability to change the used prediction model what is critical in traffic scenarios when traffic conditions have suddenly and significantly changed (e.g. incidents, weather conditions, lane closures for maintenance, etc.) [11].

MPC is applied within a rolling or moving time horizon. At each time step k a new optimization process is conducted. Optimization is conducted over the prediction horizon $\{k, \dots, k+ N_p - 1\}$ where N_p is the number of time steps in the prediction horizon [11]. Only the first of the resulting N_p control values derived from the moving horizon is applied as the control signal for VSLC. This procedure is repeated in the next time step [10] and it present the first feedback control loop in the MPC structure. Second feedback control loop is related to the optimization process for every time instant k in the rolling horizon. The MPC algorithm must find a suboptimal speed limit value in order to minimize the chosen objective function as subject to the model of the system (which can be considered as a system of equality constraints) and as subject to the safety constraint (MPC-based optimal coordination of variable speed limits to suppress shock waves in freeway traffic) [12]. The usual objective function of the MPC controller is to minimize the Total Time Spent (TTS) by all vehicles on the motorway [13]. This is done by changing the speed limit value over the moving horizon from $k+1$ until $k+N_C$. In order to improve stability and resilience to the frequently changing traffic situation it is possible to introduce a control rolling horizon with N_C number of time steps. The control rolling horizon must have fewer time instants than the original rolling horizon [16]. Optimal control signals (computed control outputs) obtained according to the predictive rolling horizon are applied in the motorway system only if they are within the trend of data from the controlling horizon. Based on heuristic reasoning it is possible to determine an initial guess for the size of the control and prediction horizons [10]. The second loop, which connects the controller based on MPC and motorway traffic system, is performed once for each time step k and provides the state feedback to the controller. This feedback corrects prediction errors and enables on-line adaptive control. In Fig. 6 schematic view of the described MPC structure is shown.

Implementation of VSLC on a motorway system is in this case considered as a nonlinear, nonconvex optimization problem, which can be solved using Sequential Quadratic Programming (SQP), the genetic algorithm and the pattern search algorithm [11]. All mentioned methodologies can be used in the optimization process in the second control loop of the described MPC structure. To determine the solution of the VSLC optimization problem is very difficult, thus, only an approximate solution can be sought. Problem is in the heavy computational burden of the optimization based approaches. In practice, it is usual to provide a synthesis of a suboptimal controller by designing an estimator of traffic conditions and a controller, which relies on the estimator for determining the control actions [15]. Example of such a suboptimal controller is the described MPC. The most widespread state estimator for nonlinear systems is the extended Kalman filter (EKF), which has been used for many applications in traffic monitoring and for incident detection [15]. To sum up, an EKF estimator computes an estimate of the traffic dynamics, which are used during computation of speed limits as the needed control output.

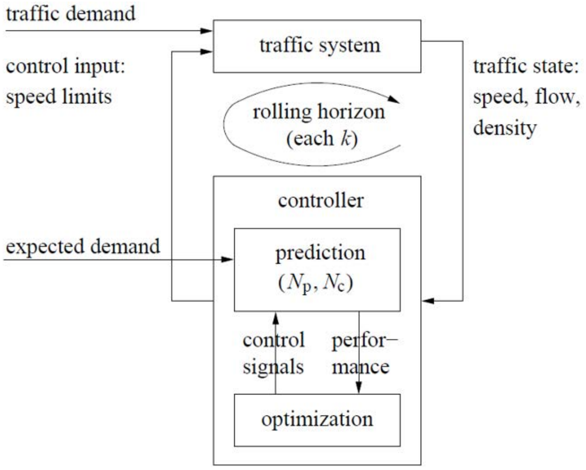

Figure 6 - Schematic view of the MPC structure [11]

5. COORDINATION WITH OTHER TRAFFIC CONTROL SYSTEMS

VSLC systems can be used in a standalone mode or in coordination with other traffic control systems. Coordination in this case means that the traffic control systems in coordination interchange traffic and control data, and use these data to improve the overall LoS on the motorway. To establish such a coordination, cooperation (communication link for data interchange) between different traffic control systems has to be established first. When

VSLC is used in coordination with other traffic control systems, better LoS on the motorway can be expected. Mostly used traffic control systems for coordination with VSLC are ramp metering and the lane change system. Additionally, today new emerging technology of connected vehicles and automated driving is being examined.

5.1 Coordination with ramp metering

Ramp metering controls the input flow from on-ramps entering the motorway mainline by the means of a traffic light mounted at the end of the on-ramp [9]. Idea is to reduce the traffic inflow if a potential congestion build-up or a congestion on the motorway is detected. The on-ramp serves as a temporally storage place for vehicles. Problems can occur when the on-ramp has to be emptied to prevent a congestion spillback into the adjacent urban road network. The vehicles from the on-ramp have in this case difficulties in merging with the motorway mainline traffic flow. VSLC can in this case reduce the speed of the vehicles on the mainline alleviating the merging process. Additionally, speed reduction by the VSLC system can also delay the mainline inflow to the merging area of an on-ramp if a congestion build-up is detected. Congestion build-up starts with a congestion pre-phase and if it can be prolonged there is a good chance that congestion can be even prevented.

To establish coordination between VSLC and ramp metering different approaches can be used. Mostly used approaches are based on fuzzy rules tuned by a genetic algorithm [16] or a neural network [19], optimal control [17] and algorithms based on the shock-wave theory [18]. In order to use one control structure for VSLC and ramp metering a cost function able to evaluate the overall LoS on the controlled motorway segment is defined. VSLC and ramp metering contribute both to this cost function and often the measure TTS is used. In this way influence of vehicles on the mainline and on the on-ramps are included in the cost function. Minimizing TTS results with maximization of the motorway throughput. Control parameters corresponding to the VLSC and ramp metering controllers are tuned based on the obtained value of the cost function. Additional variables can be also included in the cost function like on-ramp queue length, risk of traffic accidents, vehicle emissions, etc.

5.2 Coordination with the lane change system

The lane change system provides recommendations to upstream vehicles to change their lane on time before reaching a work zone, on-ramp merging point, closed lane, incident or a similar traffic situation. It is one of the most restrictive traffic control approaches but it can increase traffic safety and network throughput when combined with other traffic control systems. In [20] a combined VLSC and lane change control was tested on a truck dominant motorway segment with a closed lane. A set of rules for the lane change controller and the virtual ramp metering for VSLC were used. Simulation results showed an improvement in travel time, fuel consumption and vehicle emission values.

5.3 Coordination with automated driving

To effectively use a VLSC system an adequate percentage of driver compliance to the imposed speed limits is an important prerequisite. In some countries, this can be an issue since drivers do not comply with speed limits [22]. From this reason today vehicle control approaches based on automated and connected driving are being investigated. An on-board unit (OBU) is integrated into the vehicle enabling selected control commands to be imposed on the vehicle by overriding the driver's commands [19]. To improve the effectiveness of VSLC, automatic reduction of the vehicle's speed when it enters a zone under VSLC is needed as one of the OBU's functionalities. The vehicle obtains the information about the imposed speed limit from the traffic control system by the means of vehicle to infrastructure communication. Using this communication channel and the OBU the compliance to the imposed speed limit can be increased, especially in countries with a lower speed limit compliance rate. In [21] the approach of connected driving was implemented to harmonize the traffic speed in a work zone. The penetration rate of vehicles equipped with an OBU was also examined. Achieved results confirm that a larger penetration rate of connected vehicles, i.e. vehicles that comply with the imposed speed limit increases the effectiveness of VSLC, reduces total travel time and shortens the duration of congestions.

6. CONCLUSION AND FUTURE WORK

VSLC systems on motorways reduce the mean speed and homogenize the speeds on the mainline lanes. The results are reduced traffic jams, less air pollution, smaller possibility of traffic accidents and decreased fuel consumption. In order to achieve these effects, speed limit values have to be computed according to the current traffic situation. Therefore, a closed negative feedback control loop structure is used in which the applied control law is crucial. Appropriate control law can increase the LoS of the controlled motorway segment by affecting the fundamental diagram of the controlled motorway segment.

In this paper a short review of approaches for VSLC that are actual today is given. Simple reactive speed limit controllers are described in detail including implementation aspects. Additionally, a more complex optimization based controller based on MPC is explained. Such approach enables definition of a cost function for optimization that can contain additional quality measures related to risk of incidents, pollution, etc. For optimization, methods from the domain of artificial intelligence can be used enabling the controller to adapt itself to new traffic situations. Possibility of coordination other traffic control systems with VSLC is also examined. A description how the effectiveness of VSLC can be increased in countries with low compliance to speed limit is included. This concept is based on automated driving and a broader implementation of it can be expected in the future.

There exist also other approaches to VSLC and future work on this topic will continue with the development of a simulation framework to test the described approaches using realistic traffic data. The simulation framework will contain a module for implementation of complex control laws based on optimal control and machine learning.

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