Towards a Safe and Efficient Motorway System: Literature Review on Variable Speed Limits

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ABSTRACT: Variable speed limits (VSL) is an emerging ITS tool, which can help to improve safety and efficiency of motorway systems through a better harmonization of traffic flow. It can reduce variation in speed of vehicles travelling along the controlled section. The implementation of VSL encourages a uniform driving behavior and thus resulting in a better distribution of traffic over the motorway network, and better utilization of the road infrastructure. The primary objective of motorway traffic management is to improve mobility benefits of motorways under acceptable safety standards; this is also the main purpose of applying VSL. This paper reviews the existing VSL methods from view points of safety and mobility gains or losses due to VSL on motorway systems. A systematic review of the literature of empirical as well as simulation-based studies is presented.

INTRODUCTION

Variable speed limits (VSL) is an emerging ITS tool, which can help to improve safety and efficiency of motorway systems through a better harmonization of traffic flow. It can reduce variation in speed of vehicles travelling along the controlled section. The implementation of VSL encourages a uniform driving behavior and thus resulting in a better distribution of traffic over the motorway network, and better utilization of the road infrastructure (Hoogen and Smulders, 1994). VSL was used, for the first time, in Germany more than three decades ago.

A VSL algorithm pertains to switching of VSL controllers and applying different threshold values to change in speed limits for the VSL displays. The threshold parameters can be based on flow, occupancy level, average speed or the combination of the three. The control logic, threshold values and detector-controller layout applied to speed limiters are considered to a partially determinant factor for success of VSL (Li et al., 2015; Allaby et al., 2007). Li et al. (2014) proposed some modifications to detector location and control logic for the logic tree based VSL control algorithm proposed by Allaby et al. (2007) which is implemented in a critical section of Auckland Motorway using AIMSUN micro-simulator. They concluded that the performance of VSL is highly dependent on the control logic embedded and on the location of the VSL detectors.

VSL systems can be implemented as either mandatory or advisory. Advisory VSL systems are recommended speed limits as in the motorway E-4 around Stockholm (Nissan and Koutsopoulos, 2011); while in mandatory VSL systems, motorway users are enforced to maintain the speed displayed on variable message signs (VMS), e.g., the M25 Controlled Motorway round London (UK Highway Agency, 2004). In both cases,
effectiveness of VSL is dependent on the drivers compliance level to the speed limit value displayed on VMS (Nissan and Koutsopoulos, 2011).

The primary objective of motorway traffic management is to improve mobility benefits of motorways under acceptable safety standards; this is also the main purpose of applying VSL as mentioned before. This paper reviews the existing VSL methods from view points of safety and mobility gains or losses due to VSL on motorway systems.

**EMPIRICAL STUDIES ON VSL**

**Impacts of VSL on safety**

In the United States VSL has been implemented in a number of locations. In Tennessee, a VSL system was applied along a 19-mile section of I-75 in 1993 to deal with the reduction in visibility causing crashes during adverse weather conditions. There have been no incidents due to fog after the implementation of VSL (Robinson, 2000). In Colorado, a VSL system was applied along the Eisenhower Tunnel on I-70 west of Denver in 1995. This system aims at improving truck safety by posting vehicle-specific safe operating speeds for long downgrades. Assessment results revealed that truck-related accidents decreased on the steep downhill grade sections after the system was implemented (Robinson, 2000).

Lind (2006) investigated the impacts of VSL systems on the E6 motorway in Halland and Mölndal. The author reported that when the advisory speed limit was posted crashes were decreased by 20% and when the mandatory speed limit was posed crashes were reduced by 40%.

**Impacts of VSL on Mobility**

Van den Hoogen and Shmulders (1994) reported on the implementation of a VSL system on a 20 km long section of A2 motorway in Netherland. The system aimed at reducing the risk of shockwaves, crashes, and congestion. The authors concluded that VSL is not suitable to relieve congestion at bottlenecks as it does not increase capacity of bottlenecks.

UK Highways Agency (2004) conducted a business case to assess the effectiveness of M25 motorway in England. It is reported that there is not much change in weekday journey times while off-peak journey times increased slightly compared to the previous year. The peak one-hour throughput remained unaffected.

Papageorgiou et al. (2008) investigated the effects of VSL on the shape of the flow–occupancy diagram by using curve fitting methods. The authors reported that VSL declined the slope of flow-occupancy diagram at under-critical conditions and shifted the critical occupancy to a higher value.

More recently, Hoogendoorn et al. (2013) reported on a trial conducted on A20 near Rotterdam, Netherland starting from June 28, 2011. The authors reported that the number of vehicle loss hours decreased by 20% with 4% increase in free flow capacity at the main bottleneck.
Table 1. Summary of empirical studies on VSL.

| Location                                      | Observed impacts                                                                 |
|-----------------------------------------------|----------------------------------------------------------------------------------|
| 19-mile section of I-75, Tennessee, USA       | 5 to 10 percent reduction in speed, no crashes due to fog after implementation     |
| Interstate 270 (I-270) in Missouri, USA       | Changes in flow due to VSL were inconsistent across eight test sites              |
| Eisenhower Tunnel on I-70, Colorado, USA      | Truck-related accidents declined on steep downhill sections                        |
| A2 motorway, Netherlands                      | Severity of shockwaves and speed in all lanes were reduced                         |
| E6 motorway Mölndal, Sweden                  | Advisory = 20% crash reduction, Enforceable = 40% crash reduction, Average speed increase, Reduction in queue length |
| Motorway in Europe                            | Efficiency optimized at 50 mph. Capacity effects not clear.                        |
| A20 near Rotterdam, Netherlands               | Vehicle loss hours decreased by 20% with 4% increase in free flow capacity at the main bottleneck |

SIMULATION BASED STUDIES ON VSL

Impacts of VSL on Safety

Lee et al. (2004) employed a real-time crash prediction model integrated with a PARAMICS micro-simulator to evaluate a speed-based VSL algorithm. They concluded that total crash potential was reduced at the expense of increase in total travel time.

Abdel-Aty et al. (2008) analyzed the impacts of VSL on decreasing the risk of crashes on I-4 at different traffic conditions using PARAMICS. The authors concluded that VSL decreased the rear-end and lane-change crash risk at low volume conditions.

Allaby et al. (2007) conducted a simulation based study on 8-km section of Queen Elizabeth Way in Toronto, Canada. They reported that although the proposed algorithm improved significantly safety, it also increased total travel time for all studied scenarios.

Piao and McDonald (2008) evaluated the safety benefits of in-vehicle VSL on motorways using micro-simulator AIMSUN. The authors concluded that the implementation of VSL resulted in reduction of lane change frequency, speed differences, small time-to-collision (TTC) events and very small time headways.

Impacts of VSL on Mobility

Hegyi et al. (2005) proposed a model predictive control (MPC) method to suppress shockwaves at motorway bottlenecks. The objective of the MPC was to minimize travel time for each vehicle in the network. The results showed that the MPC relieved shockwaves for all control cases and reduced total time spent (TTS) by approximately 21% compared to no-control case.

Papamichail et al. (2008) investigated the impacts of VSL on traffic flow using a quantitative model and reported that VSL can significantly improve efficiency of traffic flow especially when integrated together with coordinated ramp metering. Carlson et al.
(2010) continued their work using a similar method and reported that VSL reduced TTS by 15.3% and improved traffic flow by lessening the capacity drop at bottlenecks.

More recently, Hadiuzzaman et al. (2012) proposed a MPC algorithm based on a modified cell transmission model to dynamically control speed. The authors reported that total travel time, total travel distance and flow were improved by 15%, 6% and 7% respectively. Islam et al. (2013) investigated safety and mobility effects of another MPC based VSL algorithm and reported that total travel time, total travel distance and flow were improved by approximately 32%, 3% and 3% respectively.

Habtemichael and Picado-Santos (2013) evaluated the performance of a flow based VSL algorithm under different traffic conditions and drivers’ compliance levels. They reported that for lightly congested and uncongested traffic conditions, they recorded travel time savings of 16% and 6% respectively. Summary of simulation-based studies on VSL is shown in Table 2.

**Table 2. Summary of Simulation-based studies on VSL.**

| Author                       | Software               | Impacts                                                                 |
|------------------------------|------------------------|-------------------------------------------------------------------------|
| Lee et al. (2004)            | PARAMICS               | Reduced average total crash potential, especially at the bottleneck. Increased the travel time |
| Hegyi et al. (2005)          | METANET                | TTS was lower and a higher outflow was achieved.                         |
| Allaby et al. (2007)         | PARAMICS               | Improved safety but increased travel time for all traffic scenarios      |
| Piao and McDonald (2008)     | AIMSUN                 | Reduced speed differences, small time headways, small time-to-collision (TTC) events |
| Abdel-Aty et al. (2008)      | PARAMICS               | Reduced rear-end and lane-change crash risk at low volume conditions. No safety benefit in congested situations |
| Papamichail et al. (2008)    | Quantitative model     | VSL can significantly improve efficiency of traffic flow especially when integrated together with coordinated RM |
| Carlson et al. (2010)        | Quantitative model     | Reduced TTS by 15.3% and improved traffic flow by lessening the capacity drop at bottlenecks |
| Hadiuzzaman et al. (2012)    | Cell transmission model| Total travel time, total travel distance and flow were improved by 15%, 6% and 7% respectively. |
| Islam et al. (2013)          | METANET                | Total travel time, total travel distance and flow were improved by approximately 32%, 3% and 3% respectively |
| Habtemichael and Picado-Santos (2013) | VISSIM           | For lightly congested and uncongested traffic conditions, they recorded travel time savings of 16% and 6% respectively. |

**DISCUSSION**

This paper reviewed empirical and simulation based studies on VSL from view points of safety and mobility gains or losses due to VSL on motorway systems. There exists a considerable discrepancy in the body of literature on VSL and no well established consensus can be reached as the findings of various authors were contradicting in several ways.
Firstly, the two main reasons behind applying VSL on motorways are to improve the safety and mobility of motorway systems. Safety benefits of VSL are well established in the literature (Hegyi et al., 2005; Allaby et al., 2007). This is apparently because of the strong relationship between vehicle speed and traffic safety. However, there is a considerable discrepancy about the mobility benefits of VSL; even though there are a number of studies that demonstrated its advantages based on empirical and simulation based research. For instance, Hegyi et al. (2005) employed second order macroscopic traffic flow model METANET to implement a MPC based VSL algorithm on a 12 km stretch of a hypothetical road network. They reported 21% reduction in total time spent (TTS) for the entire network. Long et al. (2008) conducted a similar simulation-based study using METANET model and the algorithm proposed by Hegyi et al., (2005); however they could not find any significant improvement in TTS.

Secondly, no well-established consensus can be reached on capacity changes due to VSL. For instance, Van den Hoogen and Smulders (1994) conducted a field based study using the data collected from A2 freeway in the Netherlands, where a speed-flow based VSL algorithm was implemented. They stated that no improvements were witnessed in the bottleneck capacity. Papageorgiou et al. (2008) analysed the data collected from a motorway in Europe equipped with speed-flow based VSL controllers. The results from the study were rather inconclusive concerning capacity improvements due to VSL. More recently, Hoogendoorn et al. (2013) conducted a field based study using the data collected from A20 freeway near Rotterdam in the Netherlands. The authors reported 4% increase in the bottleneck capacity after the implementation of a speed-flow based VSL algorithm.

Thirdly, the relationship between safety and mobility for VSL controlled segments are still not clear. Studies by Allaby et al. (2007) and Lee et al. (2004) showed that safety was improved at the expense of increase in travel time. However studies by Habtemichael and Picado-Santos (2013) and Islam et al. (2013) showed improvements in mobility as well as safety after implementation of VSL.

There might be several reasons for the contradictory findings reported in the literatures including different VSL algorithms applied in the literatures for varying test networks, level of driver compliance, simulation environment and assessment methodology.

REFERENCES

Abdel-Aty M., Cunningham R. J., Gayah V. V., Hsia, L. (2008) Dynamic Variable Speed Limit Strategies for Real-Time Crash Risk Reduction on Freeways. Transportation Research Record No. 2078, pp. 108-116.
Allaby, P., Hellinga, B., Bullock, M. (2007) Variable Speed Limits: Safety and Operational Impacts of a Candidate Control Strategy for Freeway Applications. IEEE Transactions on Intelligent Transportation Systems, vol. 8, no. 4, pp. 671-680.
Carlson, R.C., Papamichail, I., Papageorgiou, M., Messmer, A. (2010) Variable Speed Limits as a Mainline Metering Device for Freeways. Presented at the Transportation Research Board Annual Meeting, Washington DC, 2010 Paper #10-1529.
Habtemichael, F., Picado-Santos, L. (2013) Safety and Operational Benefits of Variable Speed Limit Under Different Traffic Conditions and Driver Compliance Levels. 92nd Annual Meeting of Transportation Research Board, Washington D.C.

Hadiuzzaman, Md., Tony Z. Qiu. (2012) Cell Transmission Model Based Variable Speed Limit Control 37 for Freeway. 91st Annual Meeting of Transportation Research Board, Washington D.C.

Han, C., Luk, J., Pyta, V., Cairney, P. (2009) Best Practice for Variable Speed Limits: Literature Review. Austroads, Austroads Publication No. AP–R342/09.

Hegyi, A., Schutter, B. D., Hellendoorn, H. (2005) Model Predictive Control for Optimal Coordination of Ramp Metering and Variable Speed Limits. Transportation Research Part C, vol. 13, p185-209.

Hoogendoorn, S., Daamen, W., Hoogendoorn, R. G., Goemans, Jan. Willem. (2013) Assessment of Dynamic Speed Limits on freeway A20 near Rotterdam, the Netherlands. 92nd Annual Meeting of Transportation Research Board, Washington D.C.

Islam, Md. T., Hadiuzzaman, Md., Fang, J., Qiu T. Z., El-basyouny, K. (2013) Assessing Mobility and Safety Impacts of a Variable Speed Limit 1 Control Strategy. 92nd Annual Meeting of Transportation Research Board, Washington D.C.

Lee, C., Hellinga, B., and Saccomanno, F. (2004). Assessing Safety Benefits of Variable Speed Limits. Transportation Research Record, 1897, pp. 183-190.

Li, D., Ranjitkar P. (2015) A fuzzy logic-based variable speed limit controller, Journal of Advanced Transportation, Vol. 49, Iss. 8, pp.913-927.

Li, D., Ranjitkar P, Ceder, A. (2014) Integrated Approach Combining Ramp Metering and Variable Speed Limits to Improve Motorway Performance, Transportation Research Record, No. 2470, pp. 86-94.

Lind, G. (2006) Weather and Traffic Controlled Variable Speed Limits in Sweden. Report, Movea trafikkonsult AB, Stockholm, Sweden.

Long, K., Yun, M., Zheng, J., and Yang, X. (2008) Model Predictive Control for Variable Speed 36 Limit in Freeway Work Zone. 27th Chinese Control Conference, p 488-493.

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

Papageorgiou, M., Kosmatopoulos, E., Papamichail, I. (2008) Effects of Variable Speed Limits on Motorway Traffic Flow. Transportation Research Record, No. 2047, pp. 37-48.

Papamichail, I., Kampitaki, K., Papageorgiou, M., Messmer, A. (2008) Integrated Ramp Metering and Variable Speed Limit Control of Motorway Traffic Flow. Proceedings of the 17th IFAC World Congress, Seoul, Korea, pp. 14084-14089.

Piao J., McDonald M. (2008) Safety Impacts of Variable Speed Limits – A Simulation Study. Proceedings of the 11th International IEEE, Conference on Intelligent Transportation Systems.

UK Highways Agency (2004) M25 Controlled Motorways. Safe roads, Reliable journeys, informed travelers. Summary Report, Issue 1.

Van den Hoogen, E., Smulders, S. (1994) Control by variable speed signs: results of the Dutch experiment. 7th International Conference on Road Traffic Monitoring and Control (CP391), pp.145-149, London, UK.