Evaluation of the Impact of Advisory Variable Speed Limits on Motorway Capacity and Level of Service

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Abstract

Variable Speed Limits (VSL) have been introduced to improve the operations of freeway facilities under congested conditions. Experience indicates that the impacts of VSL on traffic performance and safety might be higher if the displayed speed limits were mandatory instead of recommended. This paper focuses on the impact of advisory VSL and proposes a statistical methodology for the comparison of traffic conditions before and after the implementation of VSL using the prevailing flow-density relationships. A case study, with data collected from the E4 motorway in Stockholm, is used to illustrate the methodology and evaluate the impact of advisory VSL. The results indicate that the advisory VSL had no significant impact on traffic conditions, both immediately after the implementation and several months later.

Keywords: Motorway Control System; Mainline Control; Variable Speed Limits; Driver Behavior; Evaluation; Intelligent Transport Systems.

1. Introduction

Continuous changes of traffic flow and speed characteristics over space and time result in dynamic conditions leading to congestion and the build up and dispersal of queues. Considerable efforts have focused on the development of strategies and systems for dynamic traffic management as means to improve the operations of the traffic network. A range of Intelligent Transport Systems (ITS) integrated into the transportation infrastructure, for example Motorway Control Systems (MCS), have been applied as countermeasures. MCS in the form of dynamic traffic management and control systems have been developed and implemented worldwide. Examples of strategies include Mainline Control (also called Link Control), Ramp Control, Variable Speed Limits (VSL), etc. Motorway traffic management is generally based on the detection and processing of traffic characteristics such as speeds and traffic flows. This data is used as the basis for control as well as for information to the road users regarding traffic conditions.

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Variable Speed Limits (VSL) systems are an important motorway control strategy. They are used to help/demand drivers to adjust their speeds in order to better respond to changing traffic conditions downstream due to lane closures, reduced visibility and slippery road surface, developing queues, etc. In such cases VSL systems for example, display successively decreasing speed signs upstream a bottleneck. VSL have also been used on motorways to warn drivers to adjust their speeds because of adverse weather conditions, wet road conditions and darkness (Zackor, 1979), and work zones (Lin et al. 2004; Ober-Sudermeier and Zackor 2001).

In general, VSL systems can be implemented as mandatory or advisory. Mandatory systems operate as dynamic speed limits, such as the M25 Controlled Motorway round London (Highways Agency 2004), or recommended speed limits such as the MCS system in the E4 motorway in Stockholm. Reviews of practical Variable Speed Limit Systems can be found in (Robinson 2000; Wilkie 1997).

VSL, by forcing traffic to slow down in a controlled manner, has the potential to reduce congestion, shockwaves and flow breakdowns. In order to achieve this, most of the applied VSL employ an algorithm based on some threshold values e.g. traffic flow, occupancy, mean speed or a combination of them. This threshold is used as a base for deciding whether a specific speed limit should be switched on or off. These algorithms are location dependent and often demand fine-tuning. In general, two main strategies for generating VLS have been discussed in the literature. The first aims at homogenizing the flow in order to reduce the probability of breakdown (Smulders 1990), and the second aims at resolving shockwaves by limiting traffic inflow into traffic jams downstream (Hegyi 2004).

Flow homogenization strategies attempt to reduce vehicle distribution and speed differences between lanes, thereby minimizing the risk of accidents and congestion upstream of bottleneck locations (6). Under this strategy, VSL are generally applied when traffic volumes are close to capacity. There are indications that the application of VSL is useful at volumes 15-20% below capacity, (Smulders 1990). In (Smulders 1991) it is also reported that homogenization-based VSL can increase the time to breakdown but cannot suppress or resolve shockwaves.

Flow limitation based strategies for generation of VSL aim at reducing or eliminating shockwaves on freeways. These strategies attempt to reduce the lengths of traffic jams by reducing inflow. Traffic upstream is slowed down and this, in turn, reduces the inflow into the traffic jam and thereby delays the onset of congestion (Popov et al. 2008; Hegyi 2004). Hegyi (2004) claims that the problem with the homogenization approach is that the limits used are above the critical speed (i.e. the speed that corresponds to the maximal flow). On the other hand the shockwaves eliminating approach allows speed limits that are lower than the critical speed in order to limit the inflow to bottleneck areas. Hence, he proposed the Model Predicted Control (MPC) method to reduce shockwaves. The method uses a centralized controller with a macroscopic traffic model to predict the future traffic states over a prediction horizon and determine the optimal speed limits. Subsequently, a decentralized control method was also developed, that uses local information (Popov et al. 2008; Lin et al 2004). Simulation results from a case study with the A12 freeway in Netherlands show that the method successfully resolves shockwaves and reduces the total time spent by approximately 20% compared to the uncontrolled case.

In general, the impact and effectiveness of mainline control strategies have not been extensively studied and is perhaps one of the least studied areas within motorway traffic control (Messmer and Papageorgiou 1994). Kotsialos et al. (2004) report that few systematic studies have been conducted to quantify the impact of link control measures, e.g. studies such as (Zackor1979; Smulders1990). Furthermore, Messmer et al. (1994) suggest that the impact of link control has to be well understood in order to optimize the design of such systems. Similarly, the literature on evaluation of VSL systems is rather limited, both from the point of view of methods for the evaluation of such systems, and empirical evidence and systematic analysis regarding their effectiveness.

The objective of this paper is to provide a framework for the assessment of the impact of VLS and discuss its application in a case study involving an advisory VSL system in Stockholm, Sweden. The remaining of the paper is organized as follows: Section 2 reviews existing literature on evaluation of VSL, and section 3 presents a statistical methodology for the evaluation of the impacts based on before and after data. Section 4 describes the Stockholm system and applies the methodology in a related case study. Finally, section 5 concludes the paper.

2. VSL evaluation studies

The success of VSL depends to a large extent on how the drivers respond to the displayed speed limits, and their interaction with other vehicles. Various studies in Netherlands for example, suggest that speed limits were not
necessarily obeyed by drivers, most likely because the displayed speed signals were not mandatory but advisory (Remeijn 1982).

Studies on the M25 motorway in the UK (highway Agency 2004) show that safety benefits of VSL systems arise as a result of adjustments in driving behavior. Drivers kept more uniform headways, which resulted in reduced breaking. Accidents with injuries were reduced by 10%. Furthermore, traffic noise was reduced by 0.7 decibels, and fuel consumption, and thereby emissions, were reduced by 2-8% overall.

Most empirical studies of evaluation of VSL focus on their effects on several traffic characteristics using relevant data collected during periods with and without VSL. In various VSL applications lower speed differences between consecutive vehicles, speed variation, and frequency of short headways were observed. Zackor (1979) suggested that the observed changes result in an increase in safety. Due to improved flow stability the capacity also increased by 5% while the speed increased by 10%. Another study on a two-lane motorway in the Netherlands showed that on the left lane the percentage of short headways decreased significantly, leading to a smaller variance of these headways (Smulders 1992). However, mean headway on the right lane decreased, implying higher volumes. The mean speed on both lanes decreased slightly. No capacity increase was mentioned in this study.

Most of the earlier studies focused on the impacts of VSL on individual traffic variables (traffic flow distribution, mean speed, mean headway, etc). The problem with such approaches is that it is very difficult to isolate the impact of other factors that may contribute to whatever changes are observed. However, most recently, Papageorgiou, et al. (2008), examined the impact of mandatory VSL using the corresponding flow-occupancy diagram. They applied the method using flow-occupancy data before and after the implementation of mandatory VSL at a European Motorway. The VSL was using a flow/speed threshold based control strategy. The study found that VSL reduces the slope of the (flow-occupancy) graph at under critical occupancies and shifts the critical occupancy to higher values in the flow-occupancy diagram. The results from the study were not conclusive regarding the impact of VSL on the capacity of the facility. The results of the study also indicated that a VSL control strategy using the slope of the occupancy-flow curve, estimated in real time, as an indicator for VSL activation, may result in more effective and robust VSL strategies.

This paper focuses on the evaluation of an advisory VSL system implemented as part of the Stockholm Motorway Control System (MCS).

3. Evaluation methodology

With the exception of the study in (Papageorgiou et al. 2008) most of the previous empirical studies on the effectiveness of VSL focused on single measures of performance. In (Papageorgiou et al. 2008) the comparison approach was based on developing piece-wise flow-occupancy graphs and comparing the average slope of the line in the corresponding intervals for cases with and without VSL. The method used in this paper is similarly motivated as in (Papageorgiou et al. 2008) and is based on an approach first reported in (Toledo and Koutsopoulos 2004) for the validation of traffic simulation models through the comparison of simulated and actual data. Toledo and Koutsopoulos (2004) suggest the use of single-valued (e.g. speed) and multivariate (e.g. speed and density) measures of performance (MOP) for the validation of simulation models. Multivariate approaches, although desirable, are difficult to implement, unless a lot of data is available. Even if data is available potential statistical tests may violate underlying assumptions, or be too loose to be useful. In response to that Toledo and Koutsopoulos, (Toledo and Koutsopoulos 2004), propose the use of meta-models to compare results from a simulation model to actual observations. Such metamodels capture the underlying relationship between two (important) traffic variables and hence the evaluation can be based on a statistical test of whether or not the two functional forms are the same. This approach requires less data to be applied and aims at testing the structural differences in traffic conditions, as captured by the relationship between these variables.

The same methodology can be also used to test whether the introduction of VSL results to any statistically significant changes in aggregate traffic behavior. A natural selection of relationships to be tested are those related to the fundamental diagram or in general traffic stream models for the facility of interest. Such models, for example the relationship between flow and density, are representative of the characteristics of a given facility, and can be viewed as the identity of the facility. Flow-density relationships for example, capture the behavior of a facility under prevailing traffic, control, and weather conditions. Such relationships can be developed using flow-density data from before and after the implementation of VSL. Assuming the data are collected under similar conditions in terms of
weather conditions and traffic composition, the relationship should be the same, unless the implementation of VSL brings about structural changes in the way traffic dynamics develop and the facility behaves from a traffic point of view.

The proposed comparison methodology uses traffic data before and after the implementation of VSL and proceeds in two steps:

1. Specify a traffic stream model that captures the underlying relationships (consistent with traffic flow theories) between the chosen traffic variables, for example, flow \( q \) and density \( k \), \( q = f(k) \), and estimate its parameters using regression analysis and the corresponding data from before and after the VSL implementation.

2. Use statistical tests to test for the equality of coefficients across the two meta-models (corresponding to before and after conditions).

The equality of the coefficients of the models is tested with the null hypothesis \( H_0: \beta_{\text{before}} = \beta_{\text{after}} \) against \( H_1: \beta_{\text{before}} \neq \beta_{\text{after}} \), using a generalized F-test. The test uses two models: restricted (R) and unrestricted (UR). The restricted model, which forces the equality of parameters of the two meta-models, is estimated with the combined dataset (both before and after VSL). The unrestricted model is the combination of two separate models, one estimated with the before data, the other with the after VSL data.

Let \( SSE_{\text{before}} \) be the sum of square residuals when the model is calibrated with the before data, \( SSE_{\text{after}} \) the sum of square residuals with the model calibrated using the after data, and \( SSE_{\text{before}+\text{after}} \) the sum of the squared residuals when the model is estimated with the combined data (pooled before and after data). Then the test statistic \( F \) is calculated by:

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\[
EF_{K, N_{\text{before}}+N_{\text{after}}-2k} = \frac{(SSE^R - SSE^UR)/K}{SSE^UR(N_{\text{before}} - N_{\text{after}} - 2K)}
\]

\( SSE^R \) and \( SSE^UR \) are the sums of the squared residuals of the restricted and unrestricted models respectively, defined

\[
SSE^R = SSE_{\text{before}+\text{after}}
\]

\[
SSE^UR = SSE_{\text{before}} + SSE_{\text{after}}
\]

\( N_{\text{before}}, N_{\text{after}} \) are the number of observations in the before and after VSL data

\( K \) is the number of parameters in the model.

The value of the test statistic \( F_{K, N_{\text{before}}+N_{\text{after}}-2k} \) is compared against the corresponding critical value for the selected significance level in order to draw conclusions regarding the null hypothesis.

The proposed method is very flexible and may also overcome issues related to limited data availability. In many cases of evaluating VSL impacts data for many days may be available after the implementation of the VSL but not before.
Case study

The case study performed on a segment of the E4 motorway in Stockholm. E4 connects the southern and northern parts of Stockholm and is an important link to Arlanda International Airport (FIGURE 1).

Figure 1: E4 motorway system

The capacity of the E4 motorway system is constrained by its infrastructure design. A motorway control system (MCS) was implemented on the E4 in 1996 and further expanded in 2004 in order to circumvent the geometric limitations. Despite the implementation of the MCS, traffic congestion with sudden queues and serious accidents is a typical problem during morning and evening rush hours. The part of E4 where the MCS was implemented experiences the highest traffic volumes in all of Sweden.

The Stockholm VSL System

The MCS is equipped with an Automatic Incident Detection (AID), which detects serious disturbances in the traffic streams as soon as possible and automatically generates a suitable set of advisory speed limits for the approaching traffic. The recommended variable speeds limits are displayed on signs mounted on gantries every 300-500 m along the motorway. The gantries also have microwave detectors to measure traffic volumes and speeds. Detected speeds provide the input data required by the automatic incident detection (AID) algorithm. The VSL is based on closed feedback loop logic. The system is hierarchically organized with three main components (FIGURE 2), (Van Toorenburg and de Kok 1998).

- The central computer system (CS).
- Outstations (OS), each connected to two gantries with one matrix sign per lane
- Detector stations (DS) and microwave detectors

Figure 2: MCS configuration (source: (Van Toorenburg and de Kok 1998)).
The detectors have two operating modes: tracking and counting. The outstations (OS) are coupled to the gantries with one OS connected to two detector stations. The detector stations measure the velocity of each car on each lane and send it to the OS. The OS pre-processes the traffic data, and calculates the AID requests, and sends the results to the CS. The OS switches the VSL signs on its gantry, when it is instructed to do so by the CS. The CS is responsible for communicating with the outstations, processing the outstations’ AID requests, calculating the new speed limits, and sending back instructions to the OS for displaying the calculated speeds on their signs. The logic used for the calculation of the speed limits is illustrated in Figure 3. The main elements are two speed threshold values ($V_{\text{low}}$ and $V_{\text{high}}$). The observed, processed speeds are compared to these thresholds and trigger an appropriate action.

![Figure 3: Threshold values and classification of AID (source (16)).](image)

**Experimental Design**

Previously empirical studies to evaluate the performance of the system focused on comparing individual MOPs at specific locations with before and after VSL data (Nissan 2007). MOPs used include traffic flows, speeds and headway distribution. It was found that the VSL contribute to more even traffic flow distribution between lanes. However, no conclusions could be drawn regarding the overall effectiveness and impact of VSL on the operations of E4.

For this case study the section of the motorway shown in Figure 4 was used to apply the methodology presented in section 3. The segment of interest has 3 lanes per direction with a speed limit of 90 km/h throughout. For this study data were collected from the MCS detectors at the gantry locations indicated in Figure 4. The data include average speed and traffic flow in 5 minute intervals.

![Figure 4: E4 motorway section at Södertäljevägen.](image)

For the before VSL scenario data from only one day, May 25-2004, were available. After the introduction of the MCS data were more readily available. Hence, for the after the VSL scenario data from September 30-2005 (immediately after the introduction of the VSL) were used. Data were also collected during May 2005, covering the days (10, 12, 18, 26 and 31) of May. The after VSL data sets represent two different points in the operations of the system: immediately after VSL and few months later when the system is more mature and the drivers are familiar with its operations (and effectiveness) and have adapted their driving behavior. All days (before and after) had similar weather conditions (dry, no rain) Data were collected from 6:00 am to 7:00 pm.
FIGURE 5 shows the variability of speed over time for the various days for which data is available. During the evening peak period (outbound) there is a significant drop in speeds, consistently through all days, indicating severe congestion.

![Average speed over time for various days](image)

**Figure 5: Average speed over time for various days**

**Evaluation**

The methodology discussed in section 3 is used to evaluate the impact of VSL on the operation of the E4 motorway. In the first step of the methodology candidate traffic stream models representing the relationship between important variables are selected and estimated. For this study flow-density models, capturing the underlying traffic characteristics in the section of interest were developed.

Traffic stream models were first introduced as early as 1935 by Greenshield (May 1990). The initial models were single regime models using the same functional form to describe the relationship between flow and density under all traffic conditions. Edie, (May 1990), proposed the use of multi-regime models to achieve better fit to field data. Multi-regime models use different functional forms to describe the relationship between flow and density under different congestion levels.

In this study, following Eddie, a two-regime model was assumed and estimated using the before, after, and combined (pooled) data. Linear regression was performed to specify the best model and estimate its parameters:

\[
q = \begin{cases} 
  a_1 + a_2K + a_3K^2 & \text{if } k \leq 80 \text{ veh/km/lane} \\
  b_1 + b_2K + b_3K^2 & \text{if } k \geq 80 \text{ veh/km/lane}
\end{cases}
\]

Where,

- \(q\): flow (v/hr)
- \(K\): traffic density (veh/km/ 3 lanes)
- \(a_1, b_i\): parameters

The above flow-density relationships were estimated for three lanes together. FIGURE 6 illustrate the flow-density relationships for periods of before and after VSL applications and that resulted from the regression analysis and the corresponding observations.
Quantitative results of the same data shown in tables 1 (densities less than 80 veh/km and densities more than 80 veh/km) summarize the results of the regression analysis for both the restricted and unrestricted models separately for all lane. The values of the F-statistic for each case are also reported. In the case of densities of less than 80 veh/km the critical value of the F-statistic for (3, (N_{before}+N_{after}-2K) > 100) degrees of freedom at the 95% confidence level is 8.53.

Table 1: Statistics for densities < 80 and > 80 veh/km

<table>
<thead>
<tr>
<th>Case study</th>
<th>Densities &lt; 80</th>
<th>Densities &gt; 80</th>
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<tbody>
<tr>
<td></td>
<td>Residual</td>
<td>Degree of freedom</td>
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<tr>
<td>25-may 64</td>
<td>1486164</td>
<td>119</td>
</tr>
<tr>
<td>30-aug 04</td>
<td>1206686</td>
<td>112</td>
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<td>Combined case A</td>
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<tr>
<td>25-may 64</td>
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<td>119</td>
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<td>19-12-16-31 May  &amp; 2 Jun 2005</td>
<td>3967735</td>
<td>694</td>
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<td>Combined case B</td>
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<td>815</td>
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F

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<tr>
<th>Case A (density &lt; 80)</th>
<th>Case A (density &gt; 80)</th>
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<tr>
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<tr>
<td>ESSR</td>
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<tr>
<td>K</td>
<td>3</td>
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<td>ESSR-ESSR(K)</td>
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<tr>
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<tr>
<td>ESSR[V_{\text{before}}-V_{\text{after}}-2K]</td>
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<tr>
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<td>0.65</td>
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<td>ESSR</td>
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<td>ESSR-ESSR(K)</td>
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<tr>
<td>V_{\text{before}}-V_{\text{after}}-2K</td>
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<tr>
<td>ESSR[V_{\text{before}}-V_{\text{after}}-2K]</td>
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</table>
In the case of densities less than 80 veh/km the results of the before and immediately after the application of the VSL show that the null hypothesis that the flow-density relationships are the same before and after VSL can be rejected. While the results of the before and several months after application of the VSL show that the null hypothesis that the flow-density relationships are the same before and after VSL cannot be rejected. These conclusions are expected since in this regime (stable conditions) the observed speeds are between 70-100 km/h and hence the VSL system typically provides no speed recommendation.

In the case of densities greater than 80 veh/km congestion levels are high and low speeds are observed. Consequently in this range the VSL is expected to be triggered and provide speed recommendations to motorists. However, the results of the regression analysis and hypothesis testing for densities greater than 80 veh/km, summarized in Table 1, indicate in the before and (directly) after application of the VSL case the null hypothesis that the parameters of the before and after VSL that the flow-density relationships are the same before and after VSL cannot be rejected for all lanes. The results of the before and few months after application of the VSL show again that the null hypothesis that the flow-density relationships are the same before and after VSL can not be rejected for all lanes.

Conclusion

Variable message signs are implemented as means of improving traffic conditions in motorways. Previous studies have assessed the effectiveness of VSL under various conditions and operating strategies. In particular a recent study (Papageorgiou 2008) of a European implementation of mandatory VSL has shown that VSL has the potential to increase the critical occupancy. Results on the impact on capacity were not conclusive, although other studies show an increase in capacity due to VSL.

In this paper a statistical method for the evaluation of the impacts of VSL on traffic operations of a facility was presented. The method is based on the estimation of traffic stream models using data before and after the implementation of the VSL. A case study, with data from the E4 motorway in Stockholm, was conducted. The implemented VSL uses a speed-based logic and is advisory. The results indicate that VSL did not have any significant impact on traffic conditions, both immediately after its implementation and several months later.

It is important to mention again that the VSL system in Stockholm is advisory and this may contribute to the conclusions reached in this case study compared to other studies which mainly focused on mandatory systems.

After this study a detailed simulation study was also used to evaluate the impact of VSL on capacity and level of service. The results are used to draw conclusions about the sensitivity of these impacts to various parameters, especially driver compliance to the displayed speed limit.

References


