Effects of Variable Speed Limits on Motorway Traffic Flow

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Variable speed limits (VSLs) displayed on roadside variable message signs (VMSs) have emerged as a widespread traffic control measure on motorways in many countries, leading to substantial traffic safety benefits; however, there is no clear evidence of improved traffic flow efficiency in operational VSL systems. The available information on VSL impact on aggregate traffic flow behavior is summarized, and the issue is investigated in more detail with real traffic data from a European motorway. It is found that VSLs decrease the slope of the flow–occupancy diagram at undercritical conditions, shift the critical occupancy to higher values, and enable higher flows at the same occupancy values in overcritical conditions. Implications of the derived findings for more efficient VSL control strategies are discussed.

A particular control measure for traffic flow on motorways is the display of variable speed limits (VSLs) on appropriate variable message signs (VMSs) in response to the prevailing traffic conditions. In most cases, VSLs are mandatory, that is, legally equivalent to fixed speed limits, and may even be enforced to increase driver compliance and hence impact. VSL installations were first introduced in Germany more than three decades ago; today, numerous VSL installations are encountered in many European countries and in North America and elsewhere (e.g., a total of more than 800 km of VSL-equipped motorway stretches are currently in operation in Germany).

The main impact of VSLs on traffic flow is deemed to be (*1*)

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

A main targeted impact of VSLs is enhanced traffic safety, and, indeed, the selection of motorway stretches for VSL installation in several countries is guided by the frequency of registered accidents. The positive impact of VSLs on traffic safety is due to speed reduction and speed homogenization, which are correlated with a reduction in accident probability. Multiyear evaluations of VSL impact on traffic safety indicate a reduction in accident numbers by as much as 20% to 30% after VSL installation. VSLs are also envisaged by some authorities as a means to reduce vehicle emissions and road noise. Nevertheless, to the best of the authors' knowledge, there is no evaluation of the VSL impact of available installations that would demonstrate a measurable and consistent improvement of traffic flow efficiency, for example, in the sense of reduced travel times.

The ideal exploitation of the opportunities offered by VSLs would be to preserve the safety and environmental benefits offered by the current systems and to increase traffic flow efficiency. The fact that an efficiency increase could not be demonstrated in the conducted field assessments does not necessarily mean that the VSL per se is not an appropriate measure for the enhancement of traffic flow efficiency. As a matter of fact,

- The impact of VSLs on aggregate traffic behavior—for example, on the fundamental diagram (i.e., the flow–occupancy or speed–flow diagrams)—has not been sufficiently investigated with real data; as a consequence, the understanding of even qualitative (let alone quantitative) impacts of VSLs is limited to conjectures and assumptions; this lack of reliable understanding, in its turn, hinders the insightful development of VSL control strategies that would target an increase in traffic flow efficiency.
- Current VSL installations employ simple rule-based control strategies for VSL switching, which base their real-time decisions on preselected thresholds of traffic flow or occupancy or mean speed. The utilized thresholds are usually selected in an ad hoc way that does not necessarily exploit the (anyhow unknown) potential impact of VSLs on traffic flow efficiency.

The main scope of the investigations reported here is to analyze available data from a VSL-equipped European motorway so as to come up with a better understanding of the impact of VSLs on aggregate traffic behavior. The enhanced understanding of the VSL impact may eventually be exploited in order to assess and enhance the current VSL control strategies or to develop new control strategies that would target traffic flow efficiency while delivering similar benefits for traffic safety and environmental improvements as those achieved by current systems.

BACKGROUND ISSUES

Fundamental Diagram

Under the assumption that traffic conditions do not change substantially in space (i.e., along a motorway stretch) and time (e.g., because of the arrival of shock waves from downstream), traffic flow states may be approximated by the so-called fundamental diagram, which may be a flow–occupancy diagram (inverse U shape, Figure 1*a*) or a speed–flow diagram (left-turned U shape, Figure 1*b*). It should be recalled that the mean speed of a particular traffic state on the flow–occupancy diagram (Figure 1*a*) is proportional to the slope of

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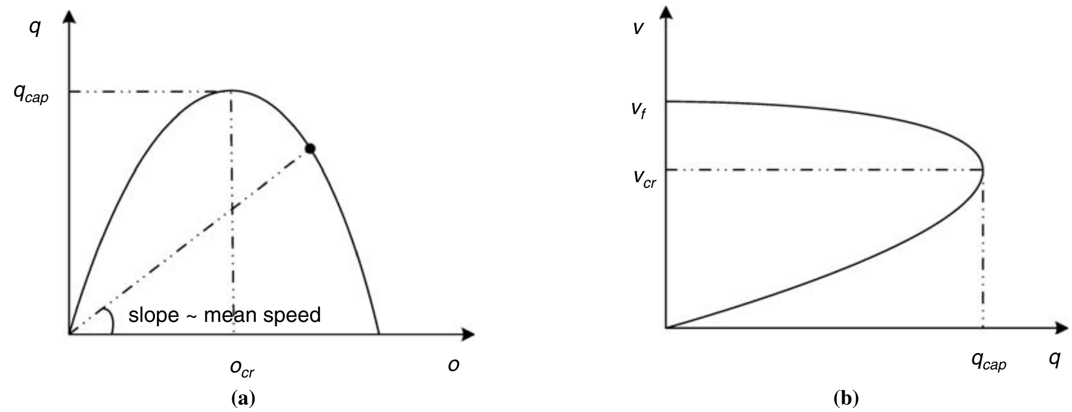


FIGURE 1 Diagrams of (*a*) flow–occupancy and (*b*) speed–flow, where q = flow (veh/h), o = occupancy (%), v = mean speed (km/h), q_{cap} = capacity flow, o_{cr} = critical occupancy, v_f = free speed, and v_{cr} = critical mean speed.

the line that connects the particular traffic state point with the origin. A fundamental diagram may be (partially) obtained by collecting measurements of the related traffic variables (flow, occupancy, mean speed) at a specific motorway location and fitting an appropriate mathematical function. This procedure, however, may lead to flawed results if the underlying spatiotemporal traffic flow phenomena are not appropriately considered. In particular, the area around the critical occupancy (capacity flow) is properly visible in real data only at active bottleneck locations [more details may be found elsewhere (*2*)].

The critical parameters (q_{cap}, o_{cr}, v_{cr}) of the fundamental diagram are not necessarily constant. Various data-driven investigations have demonstrated that the flow capacity q_{cap} may vary considerably from day to day without any obvious reason. These variations were found to be more pronounced under different weather and lighting conditions. In contrast, the critical occupancy o_{cr} (at which capacity flow occurs) was found to be less sensitive with respect to different weather conditions, and no related results are known for the critical speed v_{cr}. However, because of the relationship $q = \alpha \cdot o \cdot v$, where α is a constant, the relationship $q_{cap} = \alpha \cdot o_{cr} \cdot v_{cr}$ also exists. Then, if o_{cr} is relatively stable and q_{cap} is not, it may be deduced that v_{cr} varies as q_{cap} varies; that is, the sensitivity of this parameter to stochastic or weather influences may be similar to the sensitivity of q_{cap}. The stochastic or weather-induced change of parameters implies that the fundamental diagram may change accordingly in the short term. Moreover, various changes in infrastructure or in vehicle technology may lead to medium- or long-term changes in the aggregate traffic flow behavior.

Impact of VSLs

As mentioned earlier, there were few investigations in the past addressing the precise impact of VSLs on aggregate traffic flow behavior, for example, on the fundamental diagram. Some early investigations (from the 1970s) are summarized by Zackor (*1*) on the basis of traffic data with and without VSLs on a two-lane German motorway. The results indicate a speed homogenization effect (fewer speed differences) for individual vehicles as well as for motorway lanes under the impact of VSLs. These results are useful for a better understanding of the VSL impact on the individual vehicle speed distribution, but they do not reveal the impact of VSLs on aggregate traffic flow behavior. The latter was also addressed by Zackor (*1*) (see Figure 2*a*), but in a rather qualitative way. Figure 2*a* illustrates that

> at lower or mean traffic volumes, the mean speed is lower due to the reduction effect whereas, at higher volumes, an increase is detected due to the stabilizing effect. Thus, both capacity and speed rise by about 5% to 10% at the same time. (*1*)

Zackor (*1*) did not comment on the possible increase of the critical occupancy (or critical density) under the influence of VSLs.

The results reported by Zackor (*3*) and summarized by him elsewhere (*1*) were the basis for Cremer (*4*) to propose a quantitative model for the VSL-induced fundamental diagram change as shown in Figure 2*b*, where b is the ratio of the applied VSL divided by the free speed without VSL, and, by convention, $b = 1$ corresponds to the no-VSL case. It is quite likely that the displayed increase of flow capacity is rather exaggerated. In fact, later Dutch investigations could not identify any capacity increase that could be attributed to VSLs (*5*), albeit under advisory (not mandatory) VSLs.

In other, more recent research regarding VSL control, the assumed VSL impact was to merely replace the left part of the flow–occupancy curve by a straight line with a slope corresponding to the displayed VSL (see Figure 2*c*) (*6*).

Microscopic simulation was also used for assessing the impact of VSLs and related strategies [see, e.g., the work by Allaby et al. (*7*)].

In conclusion, there seems to be limited empirical evidence and indeed no factual consensus on the potential impact of VSLs on aggregate traffic behavior, let alone quantitatively reliable results that could be used for efficient control strategy development. Before proceeding to the analysis of available traffic data in the next sections, it is useful to summarize at this point the authors' expectations of the VSL impact along with their implications for potentially more efficient traffic flow.

Reducing Mean Speed at Undercritical Occupancies

It seems quite reasonable to assume that a VSL displayed at undercritical occupancies will reduce (with reasonable driver compliance)

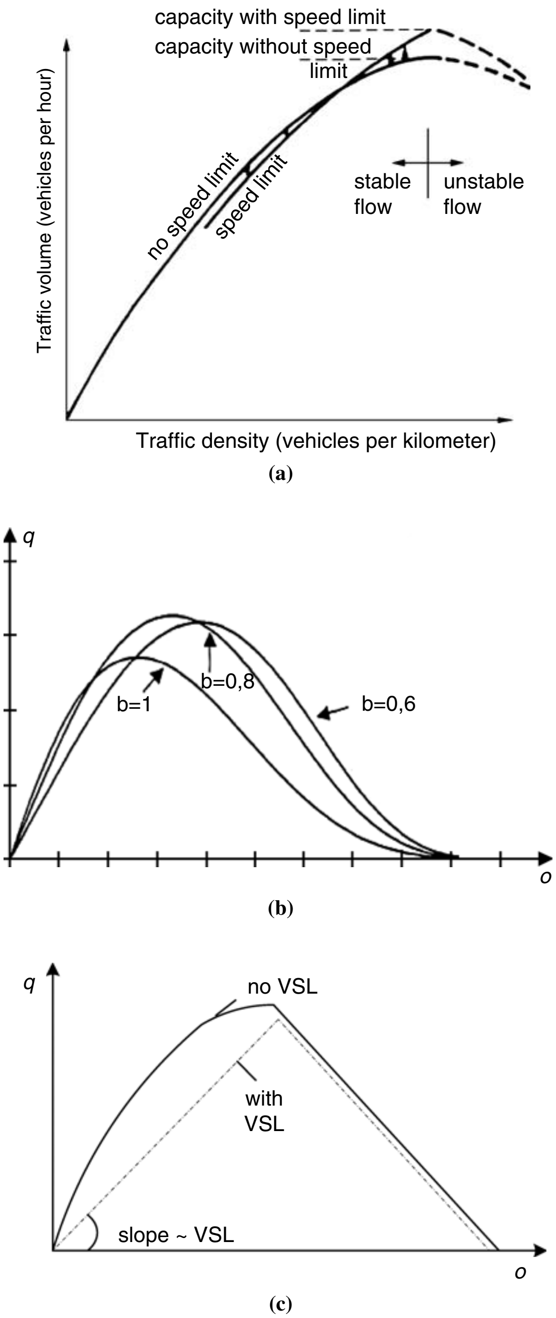


FIGURE 2 **(*a*) Change of fundamental diagram due to speed limits (*1*); (*b*) Cremer (*4*) model for VSL impact, where b = 1, 0.8 and 0.6 correspond to no speed limit, VSL = 0.8v_f, and VSL = 0.6v_f, respectively; and (*c*) Hegyi (*6*) model for VSL impact.**

the (otherwise higher) mean speed (Figure 3*a*). The magnitude of this effect is likely to depend on the displayed VSL as well as on driver compliance. The new, VSL-affected states serve the same flow at lower speed and higher occupancy than the original states, which implies that the travel time increases accordingly. Thus, applying VSLs to undercritical traffic states is likely to increase travel times and hence cause traffic flow efficiency to deteriorate.

The described state transition when VSLs are applied at undercritical occupancies could, however, be exploited in a different context. The application of a VSL upstream of a bottleneck that is close to becoming active will temporarily (for the duration of the traffic state transition triggered by the VSL) decrease the mainstream flow arriving in the bottleneck area, thus delaying the bottleneck activation and the resulting congestion. It should be noted that the temporary flow decrease during the VSL-triggered traffic state transition is due to the fact that occupancy (and density) in the VSL state is higher than in the original no-VSL state; thus, during the transition, the flow is temporarily reduced so as to create the higher traffic density of the VSL state. It should be noted that this is the only VSL impact exploited by Hegyi (*6*).

Increasing Throughput and Delaying Congestion at Overcritical Occupancies

According to Hegyi (*6*) modeling (Figure 2*c*), both curves (for VSL and no-VSL) meet but do not actually cross; Zackor (*1*) suggests that there is actually a genuine cross-point of both curves somewhere near the critical occupancy (Figure 2*a*). The cross-points (if any) are likely to lie at increasing occupancy values for decreasing VSLs because of the accordingly decreasing slope of the undercritical VSL-affected curves, and in fact there may be no cross-point for very low VSLs. When the VSL impact at occupancies near or higher than the cross-point is evaluated, the following (partly overlapping) questions are of interest (see also Figure 3*b*):

- Where is the cross point (if any) located with respect to the no-VSL critical occupancy?
- Are VSL-induced critical occupancies higher than their no-VSL counterparts?
- Are VSL-induced flows higher at overcritical occupancies than their no-VSL counterparts?
- Is there any flow capacity increase for some VSLs?

Answering these questions is crucial to the development of appropriate control strategies for VSLs capable of retarding (or avoiding) the onset of congestion.

Implications for VSL Control Strategies

The conclusions derived in the previous sections converge to the following global rules for efficient switching of VSLs:

1. VSL activation at occupancies lower than the cross-point of the VSL and no-VSL flow–occupancy diagrams decreases the traffic flow efficiency (increases travel times) unless it is used to address a downstream bottleneck and
2. VSL activation at the cross-point occupancy or (the latest) at the no-VSL critical occupancy is likely to improve the traffic flow efficiency because of avoidance or delay of congestion as well as improved traffic flow stability, which might allow for higher flows under overcritical occupancies.

These statements consider essentially one single VSL-induced flow–occupancy diagram, whereas in reality there is a series of such diagrams, one for each available VSL. However, Rules 1 and 2 above could be followed for each subsequent switching, for example, from no VSL to 60 mph, then to 50 mph, and then to 40 mph.

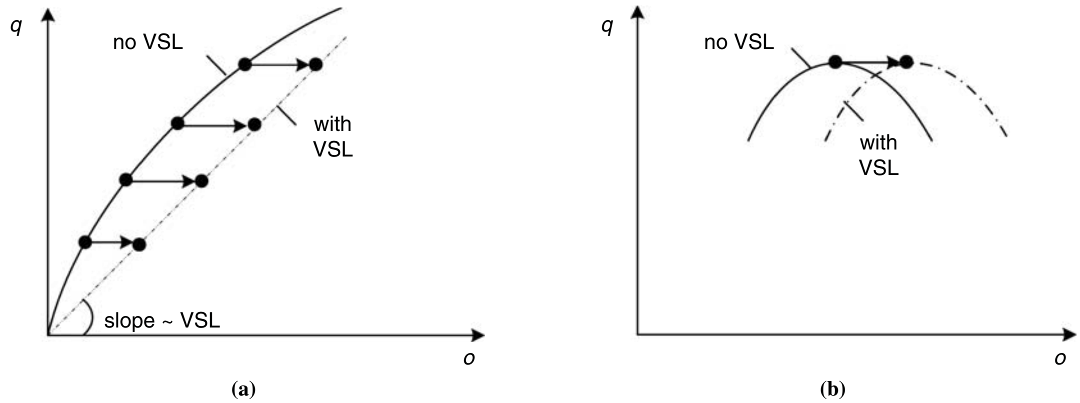


FIGURE 3 (*a*) Potential VSL impact on undercritical mean speeds and (*b*) cross-point of diagrams with and without VSL.

In conclusion, a possible VSL control strategy (practiced in many VSL installations) would call for prior determination of some thresholds reflecting those rules—for example, three thresholds for three available VSLs—and would switch the VSL in real time accordingly. Some comments are necessary with regard to this procedure:

- To avoid switching oscillations, each activation threshold should be accompanied by a different deactivation threshold so as to create a hysteresis for the switching process.
- The thresholds may be determined in terms of measured flows or occupancies or speeds or a combination thereof. Given the sensitivity of flow and speed behavior with regard to stochastic and weather conditions, it seems that decision thresholds should mostly rely on occupancies for more robust behavior that would avoid (or reduce) VSL activation too early or too late.
- The appropriate threshold values may be different from location to location, which may call for a tedious calibration procedure. It should be noted that the calibration procedure cannot be conducted before VSL installation and operation because of the need to determine the location-specific cross points of the various flow–occupancy curves.

These comments related to a potential rule-based VSL control strategy will be revisited following the presentation of the derived VSL-impact results.

MOTORWAY SITE AND DATA AVAILABLE

Motorway Site

The data used for the analysis of the effects of VSLs on motorway traffic conditions stem from both directions (three lanes each) of a motorway stretch equipped with loop detectors placed every 500 m and providing occupancy, flow, and speed measurements. A VSL control system is used that determines in real time the speed limits of this motorway stretch by providing appropriate displays to the drivers via VMSs. This control system uses a rule-based algorithm that relies on flow as well as speed thresholds. The flow and speed threshold values initially applied were revised as a result of a major fine-tuning process in January 2006, which had the effect of more frequent activation of the speed limits.

Data Treatment

Data from two different periods were available for the current study:

- May 2005 to October 2005, when the VSL control algorithm with the initial threshold values was operating and setting advisory speed limits. The utilized threshold values during this period were rather loose; that is, VSL activations were relatively sparse. This factor is beneficial for the current analysis since the 2005 data contain no-VSL measurements also at relatively high occupancy levels; and
- January 2006 to May 2006, after the major fine-tuning; during this period, mandatory speed limits were set, and threshold values for the control algorithm were rather tight.

These periods will be referred to as the 2005 period and the 2006 period for brevity. Data were available for both motorway directions, referred to as Directions A and B in the following. More details on the available data may be found elsewhere (*2*).

A first step for data treatment was to validate the available data and neglect data that were faulty or irrelevant for the current analysis. In all cases where occupancy, flow, or speed data were removed as faulty, the values were replaced by zero. Moreover, daily data that provided little or no information regarding the effect of speed limits on traffic conditions were not taken into account in the analysis (e.g., weekends, incidents).

Subsequently, the available data were classified according to the VSL that was active at the minute of data collection. More specifically, data were classified according to the VSL displayed on the first gantry upstream of the corresponding detector location, the underlying assumption being that the distance of 500 to 2,000 m between the gantry and the detector is sufficient for the drivers to adjust their speed according to the displayed VSL. The classification consisted of four cases: NSL $\hat{=}$ no speed limit, 60 mph, 50 mph, and 40 mph.

Data Analysis Methods

Since the main goal of the investigation is to examine whether the speed limits modify the shape of the flow–occupancy diagram, curve-fitting methods were used to analyze the effect of speed limits as follows. The occupancy axis was divided into intervals of equal length Δo and second-order polynomial curve-fitting was performed for each of these intervals [0, Δo], [Δo, $2\Delta o$], [$2\Delta o$, $3\Delta o$], ... At each interval, four different second-order curves were produced, each for data corresponding to different speed limits (NSL and 60, 50, or 40 mph). After different values for Δo were experimented with, it was concluded that a value of $\Delta o = 4\%$ was producing the most meaningful results. The reason for producing separate fitting curves for different Δo-regions was in order to avoid unbalanced fitting due to much higher numbers of data in some occupancy regions compared with other regions. In order to avoid the situation in which curve-fitting is using a small amount of available data, curve-fitting was actually performed in an interval Δo only if the amount of available data exceeded nine data points.

Data Selection

A total of 27 days (6 days from the 2005 period and 21 days from the 2006 period) were selected randomly for further treatment and were classified into three categories according to the weather conditions of the particular day: clear (18 days), rainy (4 days), and "?" (5 days). The last category includes days on which it was raining on and off during the p.m. peak.

Before proceeding to the evaluation of the impact of VSL control on the aggregate motorway traffic conditions, some preliminary observations regarding the particular conditions on both motorway directions may be helpful:

- The longest part of both directions of the motorway seems to resemble a motorway "pipeline" without pronounced bottlenecks and very few on- and off-ramps.
- Before the major fine-tuning, VSL activation was rather scarce; this condition enables availability of no-VSL data at and beyond the critical occupancy. After the major fine-tuning, VSL activation was more frequent than before.
- For Direction A, the main active bottleneck was always at or close to the specific data location, 441A. This situation did not occur in Direction B, where different locations were active bottlenecks on different days.

EVALUATION OF VSL IMPACT ON MOTORWAY TRAFFIC

Average Analysis

Investigation of the VSL impact on aggregate traffic flow behavior is hardly possible on the basis of individual one-day data because the critical occupancy areas, which are of most interest, frequently do not contain no-VSL data. In addition, various stochastic effects and weather conditions may distort the VSL impact, particularly with respect to the possible existence and location of cross points between no-VSL and VSL curves. In order to investigate the effect of weather conditions on the shape of the flow–occupancy diagram (with and without VSLs), three kinds of global curve-fitting by location were performed by using

- All traffic data from all 27 representative days,
- The traffic data from the 18 representative days with clear-weather conditions, and
- The traffic data from the 4 representative days with rainy-weather conditions.

Figures 4 to 7 present the curve-fitting results for different locations for the case in which all 27 representative days' traffic data are used (4*a*, 5*a*, 6*a,* and 7*a*), for the case in which clear weather traffic data are used (4*b*, 5*b*, 6*b*, and 7*b*), and for the case in which rainy-weather traffic data are used (4*c*, 5*c*, 6*c*, and 7*c*). Figures 4 and 5 refer to A-direction locations; Location 441A of Figure 4 is near the typical bottleneck of this direction, and Location 402A of Figure 5 is upstream of the typical bottleneck. In contrast, Figures 6 and 7 refer to B-direction locations, for which no typical active bottleneck location exists; that is, active bottlenecks may appear at different locations on different days.

No-VSL Data

By inspecting the no-VSL data in Figures 4 through 7, the following observations may be derived:

- The average flow capacity for both directions is slightly more than 100 veh/min for clear days but reduces to around 10% lower values on rainy days.
- The average critical occupancy for both directions is around 15% for both clear and rainy days, which indicates that the critical occupancy is not very sensitive to changing weather conditions.
- Since the critical occupancy is quite stable under different weather conditions whereas the flow capacity is not, it may be concluded that the critical speed is also sensitive to weather conditions. This observation may also be derived from the provided diagrams by connecting the origin with the corresponding (q_{cap}, o_{cr})-point and checking the slope of the corresponding connecting lines.
- The average slope of the flow–occupancy diagram at clearly undercritical occupancies ($0 \leq o \leq 10\%$) is around 8 [veh/(min · %)] for most locations and does not change on rainy days.

The last observation indicates that any change of the flow–occupancy diagram due to weather conditions occurs only around the critical occupancy region; in other words, on rainy days, the flow–occupancy curve flattens more strongly near the same critical occupancy (leading to lower flow capacity) than on clear days.

Impact on Slope at Undercritical Occupancies

Generally speaking, all diagrams confirm that the average impact of VSLs on the flow–occupancy diagram at undercritical occupancies is a visible slope decrease, the intensity of which increases with decreasing VSL. This finding is in accordance with the expectations expressed earlier.

The following more detailed observations may be made regarding the VSL impact on the fitted curve's slope at undercritical occupancies:

- The slope decrease appears to be slightly different at different locations; this difference might partly be attributed to the distance of the VSL-display gantry from the specific data location and partly to various stochastic effects.
- The slope decrease appears similar on clear and rainy days.
- The slope decrease due to a VSL of 60 mph is virtually negligible at occupancies lower than 10%; for the critical occupancy region, the impact of VSL = 60 mph is relatively small.

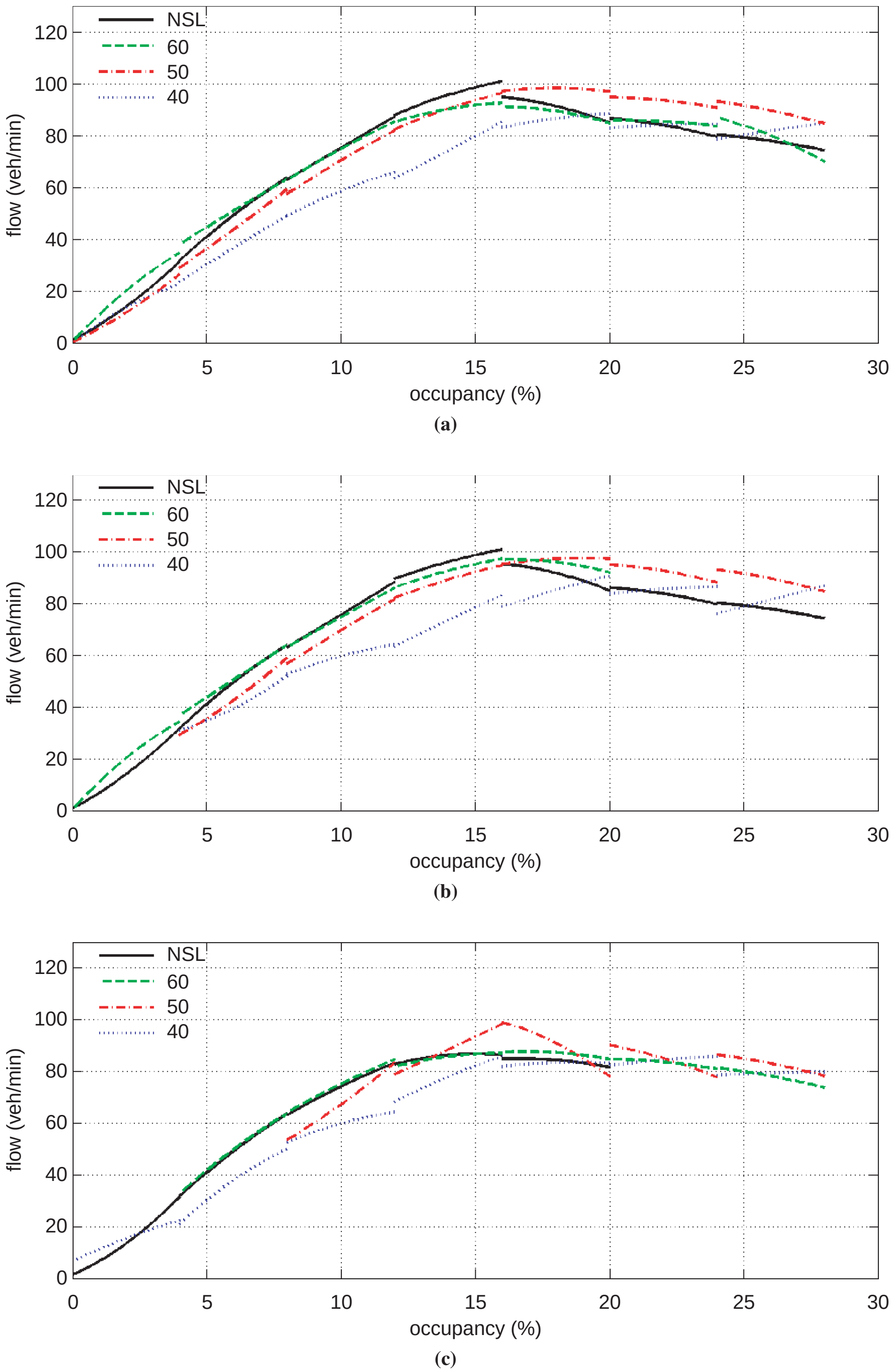
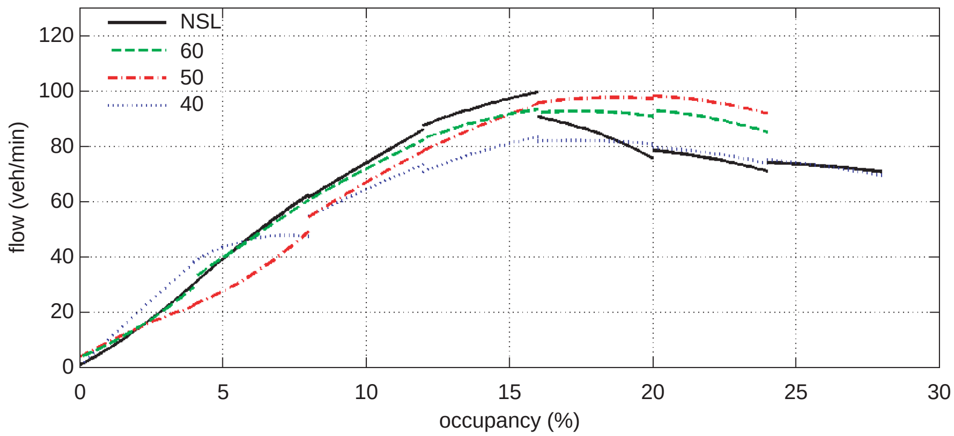
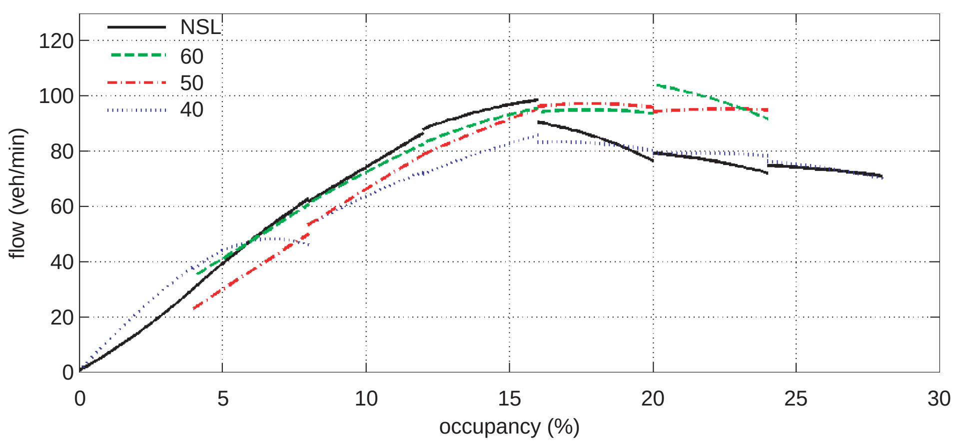


FIGURE 4 Curve-fitting results, Location 441A, for (*a*) all 27 representative days, (*b*) clear representative days, and (*c*) rainy representative days.



(a)



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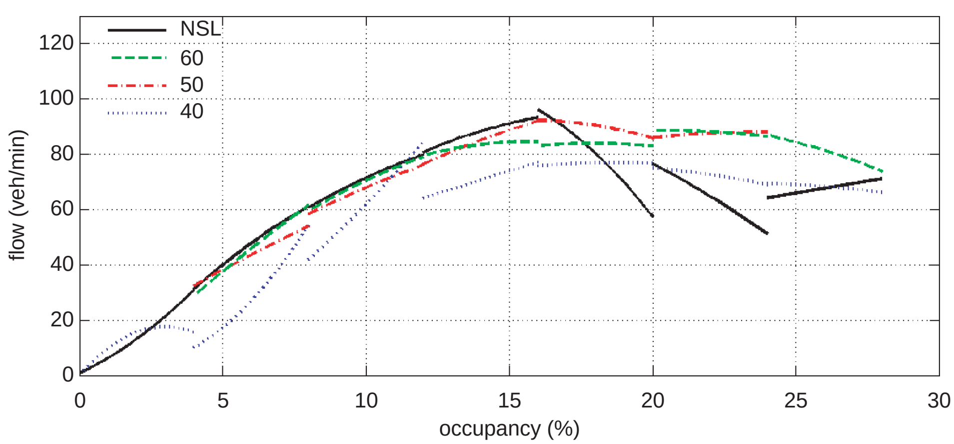


(c)

FIGURE 5 Curve-fitting results, Location 402A, for (*a*) all 27 representative days, (*b*) clear representative days, and (*c*) rainy representative days.

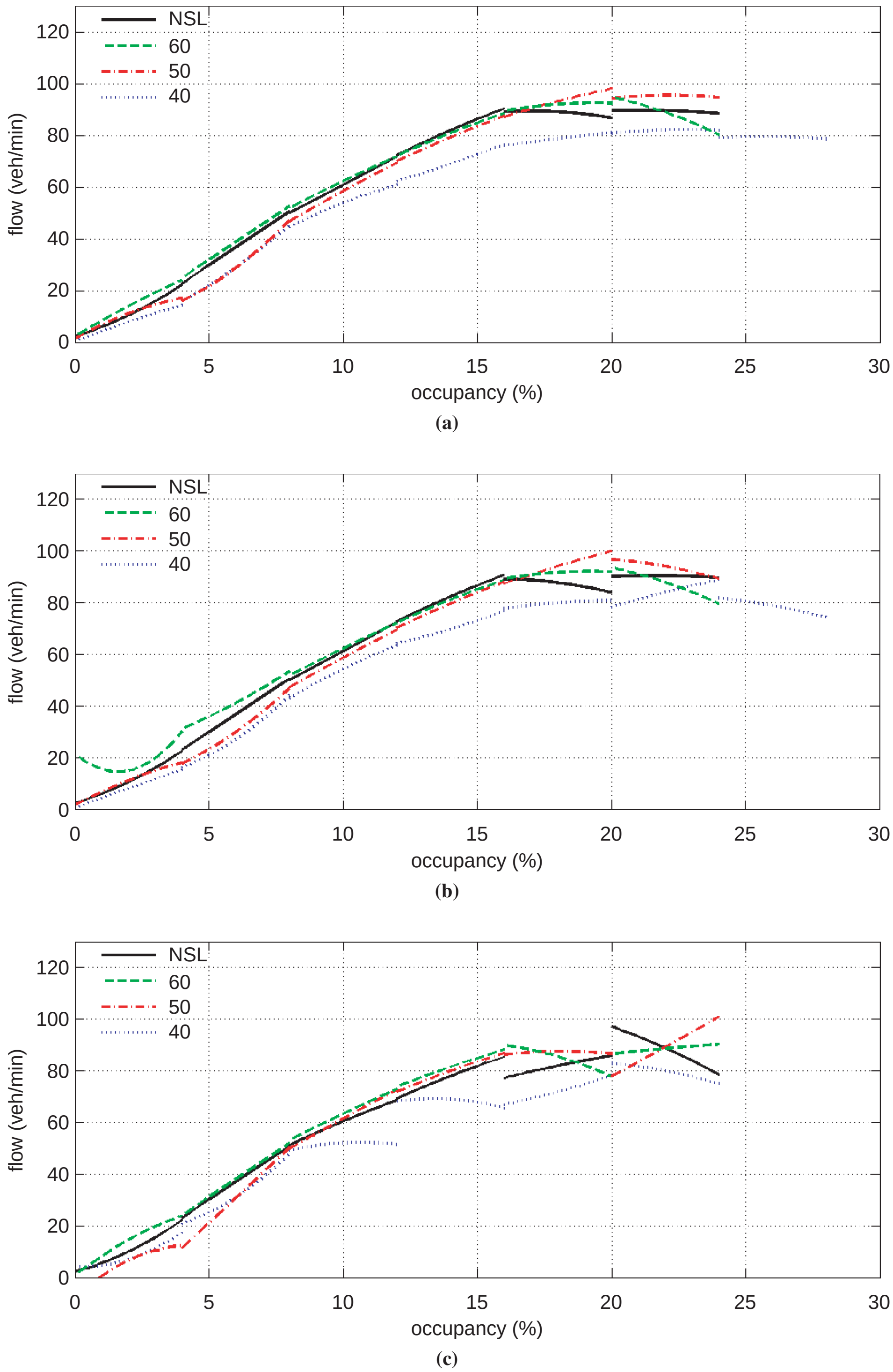
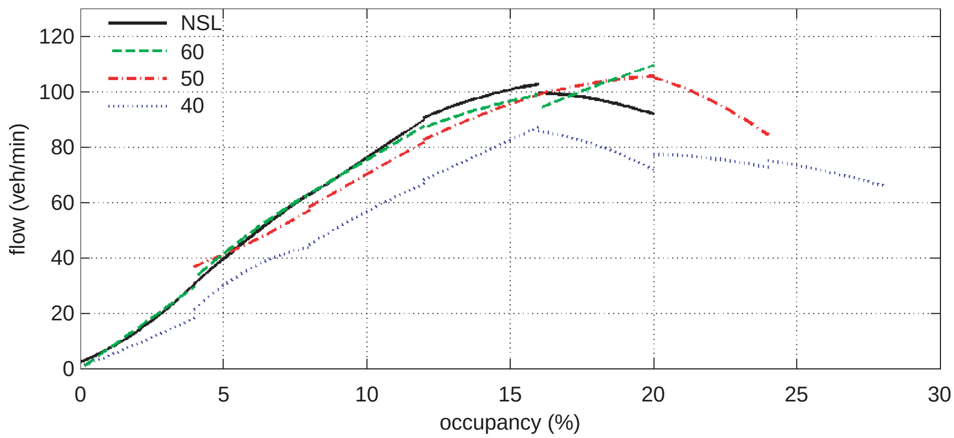
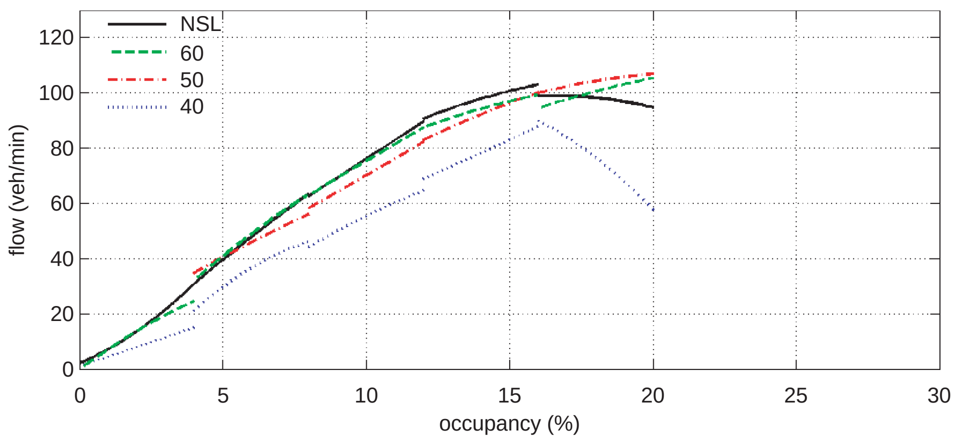


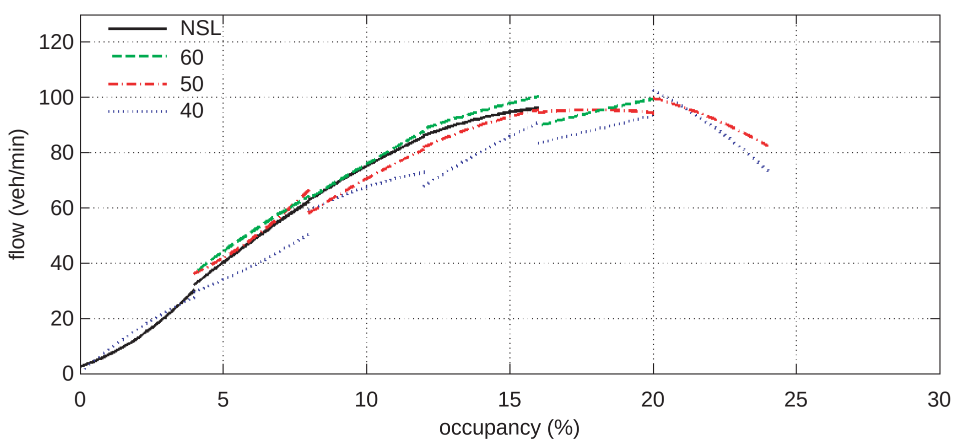
FIGURE 6 Curve-fitting results, Location 325B, for (*a*) all 27 representative days, (*b*) clear representative days, and (*c*) rainy representative days.



(a)



(b)



(c)

FIGURE 7 Curve-fitting results, Location 345B, for (*a*) all 27 representative days, (*b*) clear representative days, and (*c*) rainy representative days.

• The slope decrease due to a VSL of 50 mph or 40 mph is clearly visible at virtually all locations and all occupancy values. For undercritical occupancies in the range $0 \leq o \leq 10\%$, this decrease is from 8 (no-VSL case) to around 7 for VSL = 50 mph and around 6 for VSL = 40 mph.

Cross-Points of Curves

Various cross-points of fitted curves with and without VSLs are observed at most displayed locations. All appearing cross-points are located at or beyond the critical occupancy of 15%. The following more specific observations may be made:

• Cross-points of no-VSL with 60-mph VSL curves (if any) do not seem to be of major significance for VSL control efficiency, even for Direction A, where the impact of a 60-mph VSL is more visible in the critical occupancy area. It seems that a 60-mph VSL could be considered as a preparatory step toward a lower VSL, since it has limited impact on the aggregate traffic flow behavior for both clear and rainy days. Thus, a VSL of 60 mph could be switched on just before the critical occupancy is reached (e.g., at $o = 13\%$). There may be some merit, though, in setting 60 mph purely to reduce accidents, emissions, or noise in certain areas.

• The 50-mph VSL seems to play a crucial role for VSL control efficiency. In fact, most displayed diagrams indicate a clear cross-point of the corresponding fitted curve with the no-VSL curve on both clear and rainy days. The cross-point occurs generally at or slightly beyond the critical occupancy. At the right of the cross point, the VSL-affected flows are clearly higher (for the same occupancy values) than the no-VSL flows, although this is not always clearly visible on rainy days because of stronger scatter of the related data.

• The 40-mph VSL is probably more important for traffic safety than for traffic flow efficiency. Although some cross-points may be observed on some diagrams, no clear flow increase is visible at the right of those cross-points. Therefore, a 40-mph VSL could be switched on at clearly overcritical occupancies (e.g., at $o = 25\%$) for traffic safety considerations.

• Regarding the potential increase of flow capacity due to VSL impact, as claimed by Zackor (*1*), the analysis of the data is rather inconclusive. Some of the displayed diagrams (particularly for Direction B) indicate a possible slight increase of capacity, whereas others do not.

• The critical occupancy (at which a zero slope on the flow–occupancy diagram is attained) is shifted to higher values under the VSL impact. In particular for VSL = 50 mph, the average critical occupancy is shifted quite consistently to around 20% (from 15% without a VSL).

Daily Impact Consideration

As noted earlier, the VSL impact analysis based on individual daily data would suffer from fluctuations in aggregate traffic behavior from day to day that cannot be attributed to weather or other measurable conditions and is therefore classified as stochastic. This was the main reason for proceeding to an average impact analysis, whereby 27 days were considered simultaneously at each motorway location examined. It is, however, quite important to also examine the nature of the mentioned stochastic variations from day to day along with their possible implications for the reliability of VSL control strategies. To this end, Figure 8 shows various curves simultaneously, each fitted individually on the basis of single-day data (clear days only), for the main bottleneck location 441A.

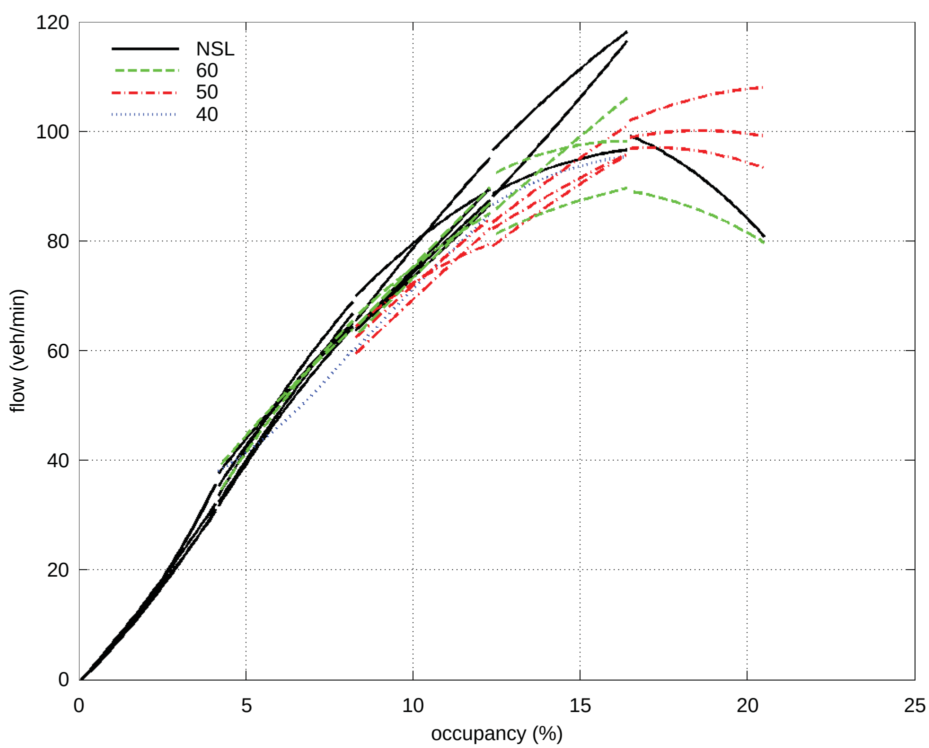


FIGURE 8 Curve-fitting results for three individual clear days (Location 441A).

The following observations can be derived from Figure 8:

• Similar fitted curves on different days are observed for each VSL value (including for no-VSL values) at clearly undercritical occupancies, that is, $o \leq 10\%$, which indicates that the mentioned stochastic effects are not significant in this low-occupancy region. In contrast, the fitted curves for the same VSL value but for different days are seen to diverge at occupancies higher than 10%.

• Flow capacity q_{cap} and critical speed v_{cr} are seen to vary from day to day. As a consequence, the use of absolute values of flow and mean speed for VSL control is not the best choice in the interest of control reliability and efficiency, since it may lead to too-early or too-late switching on and off of the VSL, according to the day of application. Some operational control strategies rely mainly on flow thresholds with supplementary information provided by speed thresholds. These control strategies may need to be revisited in the light of these findings.

• The critical occupancy is seen to be much less affected by stochastic effects; in fact, $o_{cr} \approx 15\%$ is observable on all days displayed. Thus, if the critical occupancy for a motorway location is known, decision making based on occupancy measurements and thresholds appears to be more reliable and efficient.

Implications for VSL Control Strategies

The variability of aggregate traffic flow behavior in the critical occupancy area, which was seen to occur even on days with similar weather and traffic demand characteristics, renders many currently operational VSL control strategies sensitive to the choice of the utilized flow and speed thresholds. In fact, because of the variability of traffic flow behavior, any choice of flow or speed thresholds may turn out, on different days, to be either aggressive or conservative with the risk of too-early or too-late activation.

Of course, an occupancy-based control strategy requires knowledge or accurate estimation of the location's critical occupancy. This strategy has the disadvantage—as in the case of flow and speed threshold selection—of requiring the considerable effort of estimating the critical occupancy for each motorway location; moreover, since the critical occupancy, despite being more stable, may also change because of adverse weather conditions or truck percentage changes or incidents, this approach might also be somewhat sensitive.

A real-time approach was proposed and evaluated recently for adaptively estimating the critical occupancy based on traffic measurements (*8, 9*). The approach focuses on critical occupancy estimation for ramp metering purposes and was shown to estimate quite accurately the critical occupancy at locations with significantly different critical occupancies (ranging from 18% to 27%); the adaptive approach employs a slope estimator for the flow–occupancy diagram and uses the slope estimation to eventually come up with critical occupancy estimates.

The same approach—appropriately modified—could be used by a VSL control scheme to activate a VSL around the critical occupancy. Since the focus of VSL control would be on occupancy–flow slope estimation at the current traffic conditions rather than on the critical occupancy estimation as for ramp metering purposes, only the slope estimation module of the algorithm presented by Smaragdis et al. and Kosmatopoulos et al. (*8, 9*)—appropriately modified—should be used within a VSL control strategy. Some encouraging preliminary testing results for a potential VSL control strategy based on real-time slope estimation are presented by Papageorgiou et al. (*2*). The results indicate a pertinent decision making for VSL switching (not too early, not too late), virtually without a need for calibration.

The reason why a slope-based decision procedure does not require a tedious threshold calibration for different sites, different weather conditions, and so forth is that whatever the site, weather, and further (stochastic) conditions, when the real traffic flow approaches the critical occupancy (or flow capacity) area, the slope of the flow–occupancy diagram will approach zero; thus the specification of thresholds for the slope appears easier and more general than the specification of thresholds for the absolute values of the traffic flow variables. In other words, whatever the values of q_{cap}, o_{cr}, v_{cr} of a specific location and VSL curve, the slope of the flow–occupancy diagram in that area will necessarily approach zero.

SUMMARY AND CONCLUSIONS

The effect of VSLs on aggregate traffic flow behavior (in form of flow–occupancy diagrams) was investigated on the basis of traffic data from a European motorway, where a flow–speed threshold-based VSL control algorithm is currently used. A main focus of the reported work is on verifying some long-held conjectures regarding the VSL impact on the shape of the flow–occupancy diagram.

The main findings of the reported investigations may be summarized as follows:

• Speed limits—when applied at undercritical occupancies—have the effect of decreasing the slope of the flow–occupancy diagram. Moreover, the smaller the imposed speed limit, the larger the decrease in the slope of the flow–occupancy diagram.

• The VSL-affected flow–occupancy curve crosses (at least for some VSLs) the no-VSL curve, shifting the critical occupancy to higher values in the flow–occupancy diagram. The major cross-points were found to lie on or slightly beyond the no-VSL critical occupancy.

• Regarding the potential increase of flow capacity, the data analysis was rather inconclusive, since a slight increase is indeed visible at some locations, whereas at other locations no increase can be observed.

• On rainy days, the no-VSL flow capacity and the critical speed are reduced by some 10%. The same quantities were observed to change from day to day (even for the same location) without any obvious reason (stochastic effects).

• In contrast, the no-VSL critical occupancy was found to be less sensitive to weather conditions and stochastic effects.

• A speed limit of 50 mph was found to be the main contributor to modified aggregate traffic flow behavior that could be exploited toward more efficient traffic flow. The 60-mph VSL was found to have a moderate impact, whereas the 40-mph VSL could be used at high occupancies in the interest of traffic safety rather than traffic flow efficiency.

• In view of changing real absolute thresholds of flow, mean speed, and, to a lesser extent, occupancy, a more robust and efficient algorithm might result if the decisions on VSL activation are based on real-time estimated slopes of the flow–occupancy diagram. In other words, although the motorway's flow capacity value, for example, may vary from day to day, the fact that flow capacity values occur near a zero slope does not change.

• Quite important, the real-time slope estimation algorithm is expected to reduce the effort of fine-tuning the location-dependent VSL control algorithm thresholds.

The reported results are likely to be representative for other sites in a qualitative sense since they largely conform with sparse previous observations and expectations. However, quantitative figures may be different at different sites, as with the no-VSL fundamental diagrams.

Generally speaking, the investigation of the VSL impact on aggregate traffic behavior is a difficult endeavor because data collected during specific VSL value applications may not cover the whole range of possible occupancies. Moreover, the critical occupancy area may be covered with data for all applied VSL values, but these data may reflect different traffic conditions; for example, no-VSL data in the critical occupancy area are more likely to correspond to uncongested conditions, whereas 40-mph VSL data in the same area are likely to correspond to overcritical traffic conditions, simply because the 40-mph VSL is usually not displayed at undercritical traffic conditions. In other words, the specific VSL control strategy that was active during data collection may have some impact on the derived results.

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