Dynamics of Variable Speed Limit System Surrounding Bottleneck on German Autobahn

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This paper presents findings of an ongoing empirical study focusing on identification and examination of several recurring freeway bottlenecks. It integrates the fusion of several traffic management and driver information data sources along an 18-km (11.2-mi) section of Autobahn 9 near Munich, Germany. These combined data sources further understanding of traffic dynamics and driver behavior before, during, and after bottleneck activation. The primary focus of this paper has been the investigation of variable speed limit and traveler information systems provided by means of overhead dynamic message signs so as to improve understanding of how these systems affect driver behavior and bottleneck formation and location. Toward that end, speed limit and information messages have been compared with actual traffic dynamics on the segment of Autobahn 9, and the analysis has found a strong correlation. It has been found that when drivers were warned of approaching congested conditions, the speed limit was reduced before bottleneck activation as a means of managing dense traffic. The system reduced the speed limit to control dense but still flowing traffic, and traffic continued to flow during congested periods at speeds between 30 and 40 km/h (19 and 25 mph). A comparison of sampled measurements of flow and speed with fundamental diagrams of speed–flow and flow–density indicated that speed limits were reduced. These findings will be connected to a before-and-after comparison of the system to be done to determine benefits and effects of such a system.

The objective of this paper is to compare the variable speed limit (VSL) and traveler information presented to drivers via overhead variable message signs with actual traffic conditions as determined by detailed analysis of historical inductive loop detector data extracted from a segment of German Autobahn 9 (A9) near Munich, Germany. Freeway bottlenecks are important elements of a freeway system; therefore it is important to understand their unique characteristics, in particular their causation, location, and dissipation. An active freeway bottleneck will be defined as a point on a freeway cross section upstream of which is queued traffic and downstream of which are unrestricted conditions, consistent with the definition provided by Daganzo (1). To emphasize the importance of the careful diagnosis of the causation and dissipation of bottlenecks, this analysis includes the integration of variable speed limit and traveler information data to gain important information about the dynamics of traffic flow and physical freeway infrastructure before, during, and after the activation of a bottleneck near busy freeway on- and off-ramps.

The analysis techniques used in this study include transformed curves of cumulative vehicle count and time-averaged speed versus time. These curves provided the resolution necessary to carefully and systematically diagnose bottleneck activation in both the spatial and temporal dimensions. Tutorials providing detailed descriptions of the procedures used to construct these transformed curves are shown in several references (2–5). Further, this paper builds on previous research conducted at this site, which includes a detailed examination of bottleneck activation and possible triggers (6, 7).

In Europe, VSL systems are applied in an effort to reduce vehicular crashes, postpone or prevent congestion, eliminate large speed differentials, dampen shocks, and harmonize flow during peak periods. The literature has indicated that the use of variable speed limits in Germany has decreased crash rates by as much as 20% (8). Currently, this section of A9 uses a series of algorithms to determine the most appropriate speed limit on the basis of three control strategies. These are incident detection, harmonization, and weather detection. Harmonization refers to the control of dense but still flowing traffic and is used to postpone or prevent breakdown of the facility. To date, no system such as this has been implemented in the United States; therefore this paper hopes to ignite research on the subject by means of determining whether deployment on U.S. freeways should be considered.

As anticipated, this analysis has found that there is a correlation between the variable speed limit and driver information system and the actual traffic dynamics. On the basis of sampled observations compared with the fundamental diagrams of speed–flow and flow–density, it was found that drivers were informed in advance of congested conditions and that speeds were reduced. Although speeds did decrease notably on bottleneck activation, traffic remained flowing: this may be attributable to the system’s effectiveness. Further analysis is scheduled to be conducted in the future to determine the effects of the system and its benefits.

This paper will first introduce the data sources and methodology used followed by a discussion of actual traffic dynamics as determined from detector data. Concluding sections compare the dynamics of the variable speed limit and driver information system with actual traffic dynamics to determine the correlation between them.

DATA

Fixed Sensor Data

The study site, as shown in Figure 1a, is an 18-km (11.2-mi) section of southbound A9 located near Munich, Germany. The freeway
is equipped with a surveillance system comprising dual inductive loop detector stations. The loop detector pairs (speed traps) are located in each travel lane and on freeway ramps (on- and off-), with main-line center–center spacing ranging between 340 and 1,750 m (1,100–5,700 ft). Archived data were available at 1-min sampling intervals, with vehicle count and time-averaged speed in each lane recorded separately for both trucks and automobiles. These data include directly measured vehicle speeds via the dual-loop configuration. This paper focuses on data processed for June 24, 2002, on southbound A9. In addition, data from 15 other days have been analyzed as a means of demonstrating reproducibility of findings and identifying recurring bottleneck activations at the same location over multiple days.

Variable Message Sign Data

Contributing to the overall freeway management and driver information infrastructure deployed at this site are multiple variable message signs along this segment, which are shown in Figure 1a as the vertical lines spanning the freeway cross section. These variable message signs consist of a three-sign configuration assembled on a gantry structure, a sample of which is shown in Figure 1b. VSL signs are located overhead at the center of each travel lane with a secondary sign present between each speed limit sign that contains any active warnings, prohibitions, or both for drivers (centered over lane striping). Placement of these signs is designed to ensure adequate visibility. Below this warning–prohibition sign rests a third sign that contains text and any numerics presented to the driver, such as distance to or length of incidents and congestion. Data available for this study included a log of all messages and speed limits displayed to drivers on each of the three types of signs for all 10 message sign gantries throughout the freeway segment, with a corresponding time stamp referencing deployment for June 24, 2002, southbound A9 (as well as for 15 other days). The gantries also include speed enforcement cameras in the small windows below the speed limit displays. These cameras are randomly activated; this may promote higher levels of vehicle compliance.

FREEWAY DYNAMICS

Figure 2 shows a speed contour plot for June 24, 2002, on southbound A9. With time on the x-axis, this plot illustrates average vehicle speeds measured across all travel lanes during the day at each of the 16 southbound detector stations as notated on the y-axis. Lower vehicle speeds are represented by dark shades, and faster speeds as incrementally lighter shades. Shades are interpreted between detector stations on the basis of actual speeds over detectors. Thus the speeds at each detector station are true; the intermediate shade between detector stations is the transition between true speeds. The tail of the queue can be seen propagating upstream by tracing the left perimeter of the dark portion of the plot. In fact, the shock and recovery wave passage times are marked with small ovals and rectangles, respectively, on the figure. A comprehensive analysis of oblique curves of cumulative vehicle count and time-averaged speed versus time revealed the details of bottleneck activation and deactivation times, which are also noted on the figure. Similar analyses at this site are documented for other days elsewhere (6, 7), and the method used is described in many other publications (2–5). As indicated, a bottleneck was activated between Detectors 53 and 57 at 6:33 and remained active until 10:08 when it shifted upstream between Detectors 43 and 44. The accuracy of location is limited by the spacing of main-line detector stations as shown in Figure 1a. Bottleneck analysis and triggers are not discussed in detail here, but the boundaries of the congested conditions for this day will be used as a baseline for the VSL analysis that follows.

VARIABLE SPEED LIMIT ANALYSIS

Analysis of the VSL and traveler information system focused on comparisons with actual traffic dynamics over the freeway segment before, during, and after bottleneck activation. Typical VSL sys-
tems combine the use of real-time data provided via inductive loop detectors, closed circuit television (CCTV), and remote weather information systems (RWIS) to evaluate the existing traffic, weather conditions or both as a basis for determining a recommended speed or advisory for a particular autobahn segment (8). A general approach would be to monitor traffic conditions downstream and report a lower speed or indication to drivers upstream that an obstruction exists ahead so that drivers may adjust to the situation in a suitable manner. This system implements algorithms that target incidents, weather, congestion, and potential traffic states that could lead to freeway breakdown and hazardous conditions. Currently, the detailed threshold values of the specific algorithms used are unknown; however retrieval of that information is under way. It is known that the algorithms are based on the fundamental relationships of speed, flow, and density between detector stations. Measured values are compared with threshold values, and the recommended speed, warning, or both are deployed. When critical states are identified, the system responds by reducing the speed upstream and warning drivers of the potential for breakdown. Benefits of such a system can include harmonized traffic flow, dampened shock waves, increased traffic flow, and improved safety (9). The need for lane homogeneity is heightened in Germany, where driving rules provide for separate truck speed limits and requirements for trucks and slow-moving vehicles to remain in the right lane, with the left lane reserved for passing.

VSL and traveler information data for the 10 VMS gantries on southbound A9 were analyzed for June 24, 2002 (as well as for 15 other days). Each gantry structure can display, via the three-sign configuration, a speed limit (Zulässige Höchstgeschwindigkeit), a warning—prohibition, or both accompanied by textual information for the driver. Speeds posted on the signs ranged from 60 to 120 km/h (37–75 mi/h), changing at 20-km/h (12-mi/h) increments. In this paper the SI units for the VSL displays will be used. The warning—text signs often displayed the following:

- “Achtung”—attention,
- “Ende Überholverbot”—end of all prohibitions,
- “STAU”—congestion,
- “Überholverbot LKW”—no passing for trucks,
- “Staugefahr”—warning or high probability of congestion,
- “Ende LKW Überholverbot”—end of no passing for trucks, and
- “Schleudergefahr”—slippery road.

**Corridor-Level Examination**

The two-dimensional plot of the VSL display contained in Figure 3 for the same day illustrates the varying speed limit over time and space by means of a shading system similar to that in Figure 2. The vertical bar to the right of the figure indicates the speed (km/h) of each respective shade. The respective gantry location is labeled according to kilometer marker on the y-axis, and time is shown on the x-axis. The white region indicates location at which no speed limit was posted or at which a communication failure occurred during data transfer between the field and operations center. The first dashed vertical line represents activation of the bottleneck between Detectors 53 and 57 at 6:33. The second dashed vertical line indicates the deactivation of this bottleneck at 10:08 and the activation of the

**FIGURE 2** Southbound A9 speed contour plot.
bottleneck upstream between Detectors 43 and 44. The final dashed vertical line represents the deactivation of this bottleneck at 10:30. As can be seen by comparing Figure 3 with Figure 2, there appears to be a strong correlation between the VSL and actual traffic conditions as supported by the upstream moving trend of both 80 km/h and 60 km/h speed postings on the message signs consistent with the actual movement of the shock wave representing the tail of the queue as it propagated upstream.

Interestingly, the average speed at which this 60 km/h speed limit posting propagated upstream was \(-6\) km/h (\(-3.7 \text{ mi/h}\)), and the 80 km/h speed limit posting propagated at \(-5\) km/h (\(-3.1 \text{ mi/h}\)) upstream. The 80 km/h-speed posting propagated as far as Message Sign AQ 204; the 60-km/h posting was observed as far upstream as Message Sign AQ 201; this is consistent with the propagation of the queue. The average speed of the upstream moving shock wave produced by the bottleneck activation between Detectors 53 and 57 was measured to be \(-11\) km/h (\(-6.8 \text{ mi/h}\)). The shock wave initiated by the disturbance between Detectors 53 and 57 traveled a distance of approximately 18 km (11.2 mi) before dissipating near Detector 25 close to Message Sign AQ 201. One of the anticipated benefits with the implementation of a VSL system is to dampen the effects of this upstream propagating shock wave by warning drivers of a disturbance, thus influencing them to reduce their speeds on approaching it so as to eliminate or dampen sharp reductions in speed, which could spark the shock and increase its intensity. It is questionable whether this anticipated benefit has succeeded, because large queues such as this have been observed over multiple days at this location; however flow is sustained during the congested period.

Toward further understanding of the influence of the VSL system, potential traffic state triggers that may have initiated changes in posted speeds were investigated. In addition, the posting of lower speeds downstream of the bottleneck location was compared with the arrival of the backward moving queue. This analysis focused on measured traffic dynamics near the bottleneck location. This was aimed at describing how these dynamics were then presented to drivers in relation to speeds and traffic information deployed on message signs upstream of the bottleneck location before and during activation. Several hours before bottleneck activation at 6:33, the posted speed limit was 100 km/h throughout the freeway segment, which was likely deployed because of wet-weather conditions. Historical weather data for Munich on June 24, 2002, revealed that thunderstorms were occurring after 3:00 a.m. Rain persisted until about 9:00, for a total accumulation of 30 mm (1.2 in.) for the entire 24-h period (J0). Previous studies found that wet roadway conditions can decrease capacity by as much as 350 vph and 500 vph on two- and three-lane autobahns, respectively (J1). Thus, before bottleneck activation, lower vehicle speeds were observed (as seen in Figure 2) largely because of weather conditions in combination with the lower speed limit posted and slippery road indication. It was found that flow was not restricted until 6:33.
Station-Level Analysis

As a means of examining traffic states before, during, and after bottleneck activation, Figure 4 displays transformed curves of cumulative vehicle count, \( N(x,t) - q_0 t' \), for all lanes at Detector 53. The \( N(x,t) \) are constructed so that the curve’s slope at time \( t \) would be the flow past location \( x \) at that time. This curve was plotted with an oblique axis whereby \( q_0 t' \) was subtracted from each \( N(x,t) \) to amplify the curves’ features, where \( q_0 \) is an oblique scaling rate chosen iteratively and \( t' \) is the elapsed time from the beginning of the curve. Figure 4 also includes a transformed curve of cumulative time-averaged speed at Detector 53, \( V(x,t) - b_0 t' \), where \( b_0 \) is the oblique scaling rate. The figure is further divided into two parts, \( a \) and \( b \), to illustrate different time periods. At the bottom portion of Figures 4a and 4b, both speed and warning–prohibition changes are noted as patterns for upstream Message Sign AQ 215a between 5:00 and 6:00 (upper) and 6:00 and 7:00 (lower). The legend is shown at the bottom of the figure. Figure 5 shows similar curves for Detector 47 with speed and warning–prohibition changes for nearby Message Sign AQ 214 during the same periods. These transformed curves are used to identify trends in mean measured flow and speed [slopes are labeled on the curves in vehicles per minute (vpm) and km/h] and aid in clearly identifying times at which notable flow and speed changes occurred.

![Figure 4](image-url)
Figures 4 and 5 indicate that both message signs were relatively active before the bottleneck activation at 6:33. As shown, there were noticeable flow and speed changes between these two stations, which are likely the cause of these speed and driver information changes in addition to weather conditions. As previously mentioned, at 5:00 Message Signs AQ 215a and AQ 214 displayed a speed of 100 km/h until a posting of 120 km/h was displayed at 5:25 on both signs. In fact, the speed posted throughout the 18-km (11.2-mi) segment early in the morning was 100 km/h, and the 120 km/h speed posted at 5:25 was displayed along the segment beginning at upstream Message Sign AQ 206, located 9.65 km (6 mi) upstream of the downstream-most message sign, Message Sign AQ 215a. That is illustrated in Figure 3.

Average speeds over Detector 47 are 10 km/h (6.2 mi/h) above those observed at Detector 53 during this time and average speeds over both detectors are well below 120 km/h before this increase in posted speed. As indicated, speeds at Detector 53 were below 100 km/h, and those at Detector 47 were in compliance with the posted speed. The speed differential could be directed toward extreme weather conditions such as increased rain between these two stations spaced 3.24 km (2 mi) apart. Potentially heavy movements on the freeway ramps located between these two detectors...
were investigated and found not likely to be a contributor to the speed differential at these two detectors. Investigation surrounding the speed increase found that average automobile speeds upstream at Detectors 28 through 31 near Message Sign AQ 206 were near 120 km/h several minutes before the 120 km/h speed posting on this and downstream message signs—this may have served as the trigger in response to which vehicles preferred to travel faster—or that inclement weather conditions had begun to dissipate throughout this segment. This change in speed may have been adaptive to actual vehicle speeds, because no excessive changes in traffic flow were identified around this time. However, this 120 km/h speed limit was displayed for several minutes only on Message Signs AQ 215a and AQ 214 and all message signs as far upstream as AQ 212 (see Figure 3). Vehicle speeds did not increase with the increase in posted speed along this segment. In fact, soon after, vehicle speeds decreased near Detectors 28 through 31. Several minutes before the speed reduction from 120 km/h back to 100 km/h displayed on all message signs downstream of AQ 212, observed vehicle speeds at Detector 44 (just downstream of Message Sign AQ 212) dropped to below 100 km/h. That could have contributed to the speed reductions at and downstream of this location because average speeds at Detectors 53 and 47 were already well below 120 km/h. Minutes later, Message Sign AQ 206 as well as AQ 208 and AQ 210 reduced the posted speed to 100 km/h. That could have resulted from vehicles adapting to the speed posted or the posted speeds adapting to vehicle speeds.

Displays Before Bottleneck Activation

Before bottleneck activation, at 5:43 Message Sign AQ 215a displayed a speed limit of 80 km/h followed by no speed posted 1 min later. During the time in which no speed was posted, the “congestion” indication was displayed on the textual information sign. Message Sign AQ 214 displayed a speed posting of 80 km/h at 5:44 followed by a 60 km/h speed posting 1 min later. Figure 4 illustrates that minutes before this occurrence there was a trend of decreasing average speed accompanied by increasing flow at Detector 53. The same events were observed at Detector 47 as exhibited in Figure 5. Minutes before the posting of 80 km/h, there was an observed sharp decrease in average speed [16 km/h (10 mi/h)] accompanied by two large surges in flow at Detector 47. Average vehicle speed and flow at Detector 45 were found to be similar to that observed at Detector 47. That supports the idea that the decrease in speed quite likely contributed to the dynamics between Detectors 47 and 53. The surges in flow and sharp decreases in speed most likely triggered the algorithm, seeking potential events that could spark bottleneck activation. Message Sign AQ 215 most likely displayed the congested indication because of average vehicle speeds downstream at Detector 53 almost 10 km/h lower than those observed at Detector 47.

That Message Sign AQ 215a displayed a speed of 80 km/h for 1 min before indicating congested conditions may have been triggered by average speeds dropping as low as 69 km/h (43 mi/h) the minute before. It is not known why the incremental 60 km/h speed limit was not posted. With such large incremental changes in speed (20 km/h), typical practice would consider having each speed limit displayed for a minimum period of time for safety considerations, to allow drivers to adapt to the speed change in a suitable manner (12). Several minutes later, Message Sign AQ 215a again displayed the 80 km/h posting at 5:47, most likely after detecting average vehicle speeds that remained near 80 km/h and flow that remained constant at Detector 53. At 5:48 Message Sign AQ 214 returned to a speed posting of 100 km/h after speeds remained constant above 80 km/h and flow remained stable at Detector 47. That is evidence that actual traffic conditions measured by the system triggered changes in posted speed limits. The reasons for such wide speed dynamics located between these two stations may have been inclement weather conditions, because flows were relatively moderate and heavy flows entering and exiting the freeway in the section were not present at this time. Further review of historical weather data has revealed that visibility was estimated to be 3 km around this time (10). Visibility may have been lower in this section because of potentially heavier rainfall.

Subsequent to several minutes of constant flow and speed over Detector 53, Message Sign AQ 215 increased the displayed speed from 80 km/h to 100 km/h. Shortly after, the speed was again decreased to 80 km/h at 6:15, most likely because of a surge in flow at Detector 53 beginning at 6:11. A decrease in average speed was also noted at 6:12. Message Sign AQ 214 reduced the speed displayed from 100 km/h to 80 km/h, also at 6:15. It is likely that the large surge in flow and lower average speeds at Detector 53 initiated the propagation of the 80 km/h speed posting at this time on message signs upstream of AQ 212, as presented in Figure 3.

Both Message Signs AQ 215a and AQ 214 maintained the speed posting of 80 km/h until the speed on Message Sign AQ 215a was reduced to 60 km/h at 6:36, just 3 min after bottleneck activation. Just before that, average speeds decreased to 35 km/h (21.7 mi/h), and a 35% decrease in flow over Detector 53 was detected. Upstream Message Sign AQ 214 maintained the 80 km/h posting and interestingly increased the displayed speed to 100 km/h at 6:41 before again reducing to 80 km/h 1 min later. This series follows several moments of reduced demand at Detector 47 while average speeds remained near 80 km/h. Also of interest is the display of 80 km/h increased from 60 km/h on Message Sign AQ 215 at 6:46. That came when average speeds over Detector 53 were 49 km/h (30.4 mi/h) and after a slight increase in flow.

In summary, during bottleneck formation at 6:33 between Detectors 53 and 57 the posted speed on Message Signs AQ 215a and AQ 214 was 80 km/h. On queue formation, Message Sign AQ 215 reduced the displayed speed to 60 km/h before increasing the speed back to 80 km/h. This followed an increase in flow (near that measured before bottleneck activation) observed at Detector 53 and 47. At the same time, Message Sign AQ 214 increased its posted speed to 100 km/h. Thus, on bottleneck formation vehicles were directed to increase their speeds as the queue propagated upstream from between Detectors 53 and 57. This may have contributed to the abrupt decrease in flow and speed observed at Detector 47 at 6:47 and to the sudden change of the 80 km/h speed posting to no speed posting excluding the 60 km/h step at Message Sign AQ 214. Perhaps if Message Sign AQ 214 had indicated a speed of 60 km/h in response to the low average speeds over Detector 53, the intensity of the backward-moving shock might have been reduced. Again, this shock propagated as far upstream as 18 km. Although congestion was present, flow was still sustained at low speeds [30–40 km/h (19–25 mi/h)].

Examining Traffic Parameter Relations

To understand the dynamics of the varying speed limit further, Figures 6 and 7 display the flow–density and speed–flow fundamental relationships developed for Detectors 53 and 47, respectively. Each figure is subdivided into a and b components; Figures 6a and 7a
show the speed–flow relationship and 6b and 7b show the flow–density relationship. Traffic states for each 1-min sampling period between 5:00 and 12:00 are plotted with reference to the posted speeds on Message Signs AQ 215a and AQ 214 located just upstream of the bottleneck location. Both plots show that as the freeway section approached capacity at Detector Stations 47 and 53, speeds on Message Signs AQ 215a and AQ 214 were reduced. There is a clear indication that during stable conditions the speeds of 120, 100, and 80 km/h are posted, and during unstable conditions the speed of 60 km/h and indication of congested conditions are displayed. These figures support the idea that the variable speed limit is based on the comparison of sampled values and the fundamental diagrams for this freeway segment. Further investigation is being conducted to determine the threshold values for the algorithms used.

TRAVELER INFORMATION ANALYSIS

Figures 8 and 9 illustrate the warnings–prohibitions and textual information displayed to drivers by the use of overhead message signs in time and space throughout the freeway segment for June 24, 2002, on southbound A9. The scale is consistent with figures previously described using a shading reference system that differentiates the various messages deployed. The legend identifies the proper representation of numerical values labeled on the vertical color bar. Concentrating on the two message signs (AQ 214 and 215a) upstream of the bottleneck location between Detectors 53 and 57, it is revealed that both signs displayed the “slippery road” graphic in combination with the posted speed of 100 km/h beginning at 3:20. The general practice used on this freeway section is to display symbolic or graphical notation replicating these warnings–prohibitions to reduce the amount of time for driver recognition and response as illustrated in Figure 8. Most freeway dynamic message signs in the United States do not have the capability of displaying these international symbols. The remaining message signs throughout the corridor also displayed the same posting as shown in Figure 9. Note that Message Signs AQ 202 and AQ 212 experienced a failure in communication starting at 5:00 that continued for 1 to 2 h as indicated by the dark shaded sections.

At 5:44 Message Signs AQ 214 and AQ 215a displayed the “congestion” graphic indicating that congestion was present in this section. That is 51 min before bottleneck activation between Detectors 53 and 57 and the same time that Message Sign AQ 215a changed its posting of 80 km/h to no posting and Message Sign AQ 214 changed its posting of 100 km/h to 80 km/h as discussed in the previous section. The text “Congestion” was displayed on Message Signs AQ 215a
and AQ 214, and “Slippery Road” was displayed on upstream Message Sign AQ 213 to warn drivers. This warning of congestion prevailed for only a few minutes when speeds on both message signs increased.

The “no passing for trucks” prohibition was displayed on Message Signs AQ 215a and AQ 214 beginning at 6:01. This prohibition was initially displayed on upstream Message Sign AQ 204 and propagated downstream. Truck volumes over Detectors 47 and 53 revealed that no large increases in truck flow nor trucks present in the median lane appeared to trigger this prohibition at this location. Looking upstream near Detector 30, where this prohibition was first displayed on Message Sign AQ 204, also revealed that no large increase in truck flow appeared to activate this prohibition. A potential trigger appears to be an increase in flow above a certain threshold. Surges in flow over Detector 30 appear before this time. On increasing posted speeds on Message Signs AQ 215a and AQ 214, both signs returned to posting the “no passing for trucks” prohibition until both displayed “congestion” at 6:52, 19 min after bottleneck activation. Signs AQ 215a and AQ 214 were the first to display the congestion graphic at 6:52. Both signs also indicated to drivers that congestion was present with the display of “congestion” on the text sign. Downstream Message Sign AQ 213 at this time displayed the “slippery road” text, warning drivers to use caution while advancing downstream. That also marks the time at which both message signs no longer displayed a posted speed. That followed a sharp decrease in flow and speed over Detector 47 minutes before. Message Sign AQ 215a appears to have reacted to an increase in average speed to near 60 km/h over Detector 53 by deploying the 60 km/h speed at 6:54 only to return to its previous condition on reduced speeds to 51 km/h at Detector 53.

Message Sign AQ 214 displayed the attention graphic accompanied by the “slippery road” text. This is in response to Message Sign AQ 215a decreasing its posted speed to 60 km/h from 80 km/h after bottleneck activation. Message Sign AQ 214 maintained a posted speed of 80 km/h at this time. Thus, by working in coordination, drivers were made aware of unstable conditions downstream for which congested conditions were being indicated. As mentioned earlier, this reaction is likely the result of the sharp decrease in flow and speed over Detector 53 just before this time. On increasing posted speeds on Message Signs AQ 215a and AQ 214, both signs returned to posting the “no passing for trucks” prohibition until both displayed “congestion” at 6:52, 19 min after bottleneck activation.

FIGURE 7 Detector 47–Message Sign AQ 214: (a) speed–flow and (b) flow–density relations.
CONCLUDING REMARKS

This study analyzed the dynamics of a VSL and traveler information system and actual traffic conditions leading to bottleneck activation arising on a German autobahn. Transformed curves of cumulative count and time-averaged velocity versus time were used in this study to diagnose bottleneck activation. Time–space diagrams were used to aid in the analysis of varying speed limits and driver information. Analysis has revealed that the VSL system adapted to actual traffic conditions and appeared to be sensitive to vehicle speeds downstream. That has been confirmed on other days, not described in detail here. It has also been demonstrated that measured values of flow and speed over sampling periods have been compared with the fundamental relationships of speed–flow and flow–density developed for this freeway segment to distinguish freely flowing from congested conditions. On this particular day, early activity appears to be related to weather conditions. Decreases in posted speed limits were observed primarily after observations of increasing flow accompanied by decreasing speed. Dynamics of the system closest to bottleneck activation concluded that heavy activity in both the changing of speeds and driver information was present before activation. It has been shown that coordination among the message signs is existent and that drivers are presented with both a reduced speed and the graphical representation of a disturbance ahead. Message signs closest to bottleneck activation displayed a speed of 80 km/h well before activation, which was likely deployed as a result of consistent low average speeds just upstream of the bottleneck location. Even with the reduction of speed limits, shock waves propagating a distance of 18 km were observed. Further research is under way to document these phenomena for other days and other circumstances with a before-and-after comparison of the system. Lessons learned will be helpful because VSL systems are being considered for deployment in the United States. This paper demonstrates a useful procedure for analyzing VSL and traffic information systems, which can be replicated elsewhere if archived surveillance system data are available.

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