Using ITS Data Fusion to Examine Traffic Dynamics on a Freeway with Variable Speed Limits

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Abstract—This analysis focuses on an 18-km section of Autobahn 9 (A9) located between Munich and Nurnberg, Germany. This section of freeway not only has an extensive surveillance system, but also contains a variable speed limit and congestion level information system using variable message signs. Analysis focuses on the activation a bottleneck that occurs in the southbound travel direction near the vicinity of freeway on and off-ramps. Transformed curves of cumulative vehicle count and time averaged speed are used to reveal the resolution necessary to determine important traffic flow features prior to bottleneck activation. Analysis of variable speed limit, congestion level information, weather, and floating car data will be used to gain important information about the dynamics of traffic flow and physical freeway infrastructure prior to bottleneck activation.

I. INTRODUCTION

The objective of this paper is to locate and analyze dynamic traffic features surrounding an active bottleneck along an 18-km section of Autobahn 9 (A9) between Munich–Nurnberg, Germany. An active bottleneck is defined as a point on a freeway upstream of which is queued traffic and downstream of which are unrestricted conditions, consistent with the definition in [1]. The study section is located between southbound km markers 510.34–528.15 (Fig. 1). There are 16 inductive loop stations (labeled 25–57) and 10 dynamic message signs (labeled AQ 201–215a) located overhead as dark lines spanning the lanes in Fig. 1. These dynamic message signs provide drivers with queuing and congestion characteristics, the current speed limit and passing restrictions, which vary throughout the day.

Past studies have analyzed traffic features both upstream and downstream of freeway bottlenecks, mainly at sites in North America [2,3,4,5,6,7,8]. Here there is an opportunity to add to the previous literature by describing the reproducible features of freeway bottleneck activation and deactivation on a German freeway. The analysis methods used historical inductive loop detector data to determine potential dynamic traffic features that triggered the activation of a bottleneck and characteristics of the bottleneck as it impacts travel upstream and downstream the mainline. Analysis also included the fusion of historical variable message sign, floating car, weather and variable speed limit data to begin an assessment of their relationships, interactions and accuracy compared with actual traffic flow as measured with the inductive loop detector data. Analysis and results focus on the visual representation of each through the construction of visually enhanced plots.

II. METHODOLOGY

In order to observe how queued and unqueued traffic states changed between measurement locations and over time, transformed curves of cumulative vehicle arrival versus time and transformed curves of cumulative time-average velocity versus time were constructed using historical inductive loop detector data in the form of vehicle count and speed per unit of time. These transformed curves provide visual representation of flow characteristics that cannot be visually identified otherwise. Detailed descriptions of the procedure used to construct these transformed curves are shown in several references [9,10].

Time-space diagrams were also used to determine average velocity (slope) of a vehicle (floating car) as it traveled along the study section. Visual representation of the accuracy of congestion parameters indicated to vehicle drivers by overhead variable message signs were used to assess whether the estimated parameters were consistent with the traffic conditions as indicated by the inductive loop detectors.

The speed limits indicated on the variable message signs within the study area were plotted to indicate the posted speed throughout the corridor during bottleneck activation.
appears to remain active between upstream and higher speeds just before 9:30 when it shifts distance of approximately 14 km. Later in the morning period, which is a disturbance can be traced upstream to freeway minutes after. The disturbance then appears to shift both upstream and downstream of the freeway minutes after. The disturbance can be traced upstream to stations 34 (km marker 516.100) early in the morning and traced as far back as station 28 (km marker 513.280) later in the morning period, which is a distance of approximately 14 km. Once the suspected bottleneck shifts downstream to between stations 57–53, it appears to remain active until just before 9:30 when it shifts upstream to between stations 53–47, as indicated by low average speeds upstream and higher speeds downstream. The potential bottleneck appears to remain active between stations 53–47 until around 10:00 when free flow speeds are again visible throughout the corridor.

This figure helps to display the length and duration of congestion (slow speeds) and serves as a visual map of vehicle queuing, shown by the black shaded area, upstream from the potential active bottleneck locations. The assumptions stated here are based on average speed only as this plot serves as a guide for further analysis to determining actual bottleneck location and activation times which are discussed in the following paragraphs.

To study the average speed for all vehicles over all lanes in the study area, a set of oblique \( V(x,t) \), cumulative curves of time-averaged velocity (over all lanes at each station) were constructed in Fig. 3. The \( V(x,t) \) ordinate is established by plotting cumulatively the time-averaged velocity for each averaging period (1 minute). The \( V(x,t) \) values were then plotted on an oblique axis by subtracting a value \( bo \) from each value, where \( bo \) was an oblique scaling rate and \( t' \) was the elapsed time from the beginning of the curve. These oblique curves are used to identify trends in mean measured velocity and to clearly identify times at which notable velocity changes occurred [8,9].

By examining the slopes of each curve, this figure shows nearly constant speed at station 57 from 5:30–11:00. The average speed measured detector 57 is above 90 km/hr. Looking at the stations near the suspected bottleneck location, a trend in decreasing average speed is visible at stations 53–47 around 6:00. There are multiple freeway on and off-ramps just upstream and downstream of these stations (Fig. 1). From this location, drops in average speed can then be traced at stations further upstream. Substantial

III. FIXED SENSOR DATA ANALYSIS

Inductive loop detector data in 1-minute increments for May 21, 2003 included both vehicle count and average speed by lane and vehicle type (truck versus auto) over the time interval. The data were available at 16 southbound stations (25–57) in the A9 study area. Using the average speed for all vehicles over all lanes provided by the loop detector data; a speed contour plot was constructed between 5:30–11:00 (Fig. 2). The stations are indicated on the y-axis with their respective km marker and time on the x-axis. The scale uses a color reference system in which dark shades indicate slower speeds and light shades indicate faster speeds.

Looking at average speed over all lanes, there is a potential bottleneck appears to be initially activated between stations 53–47 (km markers 526.400–524.010 respectively) beginning around 6:30 as indicated by the decrease in average speed over all lanes (black shaded area). This disturbance then appears to shift both upstream and downstream of the freeway minutes after. The disturbance can be traced upstream to stations 34 (km marker 516.100) early in the morning and traced as far back as station 28 (km marker 513.280) later in the morning period, which is a distance of approximately 14 km. Once the suspected bottleneck shifts downstream to between stations 57–53, it appears to remain active until just before 9:30 when it shifts upstream to between stations 53–47, as indicated by low average speeds upstream and higher speeds downstream. The potential bottleneck appears to remain active between
speed reductions are seen as far upstream as stations 34 and 28 and downstream to station 53 as was indicated in Fig. 2. It appears that maximum average speeds between stations 25–45 were well above 100 km/hr, while maximum average speeds between stations 47–57 were below 100 km/hr even when free-flow conditions were present. Vehicles traveling southbound reduced their speeds beyond station 45. This may be due to the variable speed limit posted in this section or due to the lane drop (from 3 to 2 lanes) between stations 44–45.

Beginning at stations 53–47, a decrease in average speed was evident followed speed decreases successive upstream loop detector locations shortly after. In order to further investigate these speed reductions, oblique $V(x,t)$ and oblique $N(x,t)$ were constructed to determine relationships between trends in flow and average speed. Each $N(x,t)$ contains cumulative counts measured across all freeway lanes at each station. While an unaltered $N(x,t)$ would be a step function with equal time steps, the curves shown in Fig. 4 are linear interpolations through the top of each step so that the curve’s slope at time $t$ would be the flow past location $x$ at that time. With a construction process similar to that used for oblique $V(x,t)$, the $N(x,t)$ values were then plotted on an oblique axis by subtracting a value $qd'$ from each ordinate, where $q_o$ was the oblique scaling rate and $t'$ was the elapsed time from the beginning of the curve.

Fig. 4 contains the oblique $N(x,t)$ (left axis) and $V(x,t)$ (right axis) for station 57 between 5:30–11:00. This figure confirms the nearly constant speed of over 90 km/hr at this station between 5:30–11:00. During this period, the flow increased to 2904 vehicles per hour (vph) and there were no disturbances or large fluctuations during the analysis period. This verifies that traffic remained freely flowing at station 57 and that the suspected bottleneck was located upstream.

For station 53 Fig. 5 reveals that at 6:04, a decreasing speed trend was accompanied by a large increase in flow. At 6:44 there was a notable speed drop in speed accompanied by a slight flow drop. This speed decrease could be due to heavy ingress and egress (weaving) at the downstream on and off-ramps. The relatively high flow combined with low speeds represents congested conditions, indicating that the bottleneck is located between stations 57–53. To confirm this, Fig. 6 (station 47) demonstrates that at 6:06, there was a slight decrease in speed accompanied by a large flow increase. At 6:32 there was a sharp speed drop which could be caused by a surge in flow at the nearby on-ramps (detector data were not available). At 6:35, speeds increased until 6:49 when a sharp speed decrease was accompanied by a slight flow decrease. At 7:26, there was a sharp flow decrease, marking the arrival of the tail of the queue from the bottleneck located between stations 53–57. Speed decreased at 6:49, while a notable flow drop occurred at 7:26. Using a figure not shown here, the tail of the queue arrived at station 45 at 6:06. Sharp decreases in speed and flow were observed at 6:37. As observed at station 47, speed and flow increased at 6:49 before decreases at 7:04. These times and locations were mapped in Fig. 2, which shows that this shock then propagated upstream to station 34 by 6:55.

These details provide evidence of a bottleneck being activated between stations 57–53 at approximately 6:04. This bottleneck remained active until 8:41 when it shifted upstream to the segment between stations 53–47. The bottleneck was deactivated at 9:58. Discharge flow is shown on Figure 3. The average shock speed was measured as -21 km/hr.
With a suspected bottleneck activation now confirmed, its probable causes were analyzed. Notice in Fig. 2, the freeway on- and off-ramps between stations 53–57 and the on-ramps up- and downstream of station 47. Oblique $N(x,t)$ for the on- and off-ramp between stations 57–53 were constructed (not shown here). A surge in on-ramp flow was observed at 6:01. The speed of entering vehicles was 52 km/hr compared to 82 km/hr observed at station 53. This surge in slow-moving entering traffic may have disrupted flow. A surge in exiting vehicles (to 1620 vph) was observed at 6:10. The resulting weaving maneuvers may have triggered the bottleneck activation between stations 53–57.

Analysis of truck behavior between detectors 47–57 (figures not shown here) revealed that median lane truck flow at station 53 peaked at 6:12 when 11 trucks/min were observed until 6:52. Truck flow in the right lane peaked at 6:07, with 8 trucks/min observed until 6:17. This large increase in truck flow in the median lane over station 53 minutes after the bottleneck activation may indicate that trucks were merging into the left lane due to the higher volumes of merging traffic on the ramps between stations 57–53.

Truck analysis at station 47 revealed low truck flow in the median lane (1 truck per minute) between 5:58–8:23. In the right lane, 6 trucks/min were observed. A large truck flow was present in the left lane at station 53 and a low truck flow in the left lane at station 47. This may indicate that trucks were merging to the right after passing station 47.

Further analysis of the possible causes of bottleneck activation is continuing. Analysis of bottleneck activation during the evening peak period will also be investigated.

IV. FUSION OF OTHER DATA SOURCES

A. Variable Message Sign Data

Variable message sign data from six locations were analyzed from May 21, 2003 (see Fig. 2). Data recorded for each sign includes the estimated length of congestion, in the form of km-km marker, and the duration for which the estimated congestion was present. The estimated length of congestion was rounded to the nearest km. The estimated congestion parameters provided by the message signs were plotted as rectangles over the speed contour plot as shown in Fig. 7. The first message was reported on the sign at km 522.8 (AQ213), between stations 47–45. This message was deployed at 6:38:41 and indicated a slow down (congestion) over a length of 3 km (km 526.973–523.973) between stations 57–47. This message was deployed approximately 34 minutes after the initial bottleneck activation between stations 57–53 and was posted until 6:42:37. Table 1 summarizes the variable message sign data for the day. A total of 70 messages were deployed, 44 of which between 5:30–11:00. When deploying messages about congestion, it is important to inform drivers about the congestion beforehand so they may anticipate the shockwave traveling upstream in a suitable manner. Table 1 shows the average distance between the downstream estimated queue indicated by the sign from the location of the variable message sign where drivers received the message. Nearly all messages displayed congestion downstream, except for the message deployed by sign AQ204 between stations 28–30.

It appears that the congestion parameters are estimated well as indicated by the shape of the parameters and the speed contour plot. However, the length of congestion is both under and over reported during certain periods and is shifted forward in time. This may be due to the fact that the system may calculate congestion parameters based on previously measured data, causing a delay with computation and output, and the distance is estimated to the nearest km.

B. Floating Car Data

Data from a vehicle equipped with a global positioning system (GPS) were provided. Data consisted of distance

<table>
<thead>
<tr>
<th>Floating Car</th>
<th>Time Beginning</th>
<th>Time Ending</th>
<th>Distance Traveled (km)</th>
<th>Average Speed (km/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run</td>
<td>8:02:54</td>
<td>8:28:47</td>
<td>14.87</td>
<td>36.12</td>
</tr>
<tr>
<td>2</td>
<td>10:57:01</td>
<td>11:06:37</td>
<td>14.87</td>
<td>94.83</td>
</tr>
</tbody>
</table>

TABLE I

VARIABLE MESSAGE SIGN SUMMARY (5:30–11:00)

<table>
<thead>
<tr>
<th>Message Sign</th>
<th>Location (km marker)</th>
<th>Number of Messages Displayed</th>
<th>Dist between indicated congestion and sign (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AQ 204</td>
<td>514.2</td>
<td>1</td>
<td>-0.38</td>
</tr>
<tr>
<td>AQ 206</td>
<td>515.22</td>
<td>9</td>
<td>2.05</td>
</tr>
<tr>
<td>AQ 210</td>
<td>519.35</td>
<td>10</td>
<td>0.80</td>
</tr>
<tr>
<td>AQ 212</td>
<td>521.20</td>
<td>17</td>
<td>0.74</td>
</tr>
<tr>
<td>AQ 213</td>
<td>522.80</td>
<td>5</td>
<td>1.53</td>
</tr>
<tr>
<td>AQ 214</td>
<td>524.05</td>
<td>2</td>
<td>1.16</td>
</tr>
</tbody>
</table>
traveled (km) and speed recorded every 1 second. Two travel runs in the southbound direction along A9 between stations 28–57 from 8:00–8:30 and 10:56–11:08 were available. The trajectory of the first vehicle passed through congested conditions and is shown in Fig. 8 (the color is opposite to the speed contour map with dark for high and light for slow speeds). The floating car runs are summarized in Table 2.

### Table 2

<table>
<thead>
<tr>
<th>Detector-Detector</th>
<th>Travel Time</th>
<th>Average Speed (km/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>28-30</td>
<td>0:00:35</td>
<td>93.36</td>
</tr>
<tr>
<td>30-31</td>
<td>0:00:26</td>
<td>93.30</td>
</tr>
<tr>
<td>31-34</td>
<td>0:00:47</td>
<td>97.29</td>
</tr>
<tr>
<td>34-35</td>
<td>0:00:47</td>
<td>108.73</td>
</tr>
<tr>
<td>35-36</td>
<td>0:00:40</td>
<td>104.93</td>
</tr>
<tr>
<td>36-39</td>
<td>0:01:23</td>
<td>104.87</td>
</tr>
<tr>
<td>39-40</td>
<td>0:01:04</td>
<td>86.60</td>
</tr>
<tr>
<td>40-43</td>
<td>0:01:16</td>
<td>79.85</td>
</tr>
<tr>
<td>43-44</td>
<td>0:04:11</td>
<td>16.02</td>
</tr>
<tr>
<td>44-45</td>
<td>0:01:34</td>
<td>25.93</td>
</tr>
<tr>
<td>45-47</td>
<td>0:08:05</td>
<td>10.79</td>
</tr>
<tr>
<td>47-53</td>
<td>0:05:37</td>
<td>27.02</td>
</tr>
<tr>
<td>53-57</td>
<td>0:01:28</td>
<td>72.04</td>
</tr>
</tbody>
</table>

As shown, the congested conditions experienced by the first floating car added 0:16:17 of travel time. Further analysis was conducted to determine the speed and travel time between stations to determine where the highest levels of congestion were present. Table 3 shows the average travel time and speed between stations for the first floating car.

The floating car experienced relatively high speeds until reaching station 40. Here, the speed of the vehicle began decreasing as it entered congested conditions. This is noticeable in Fig. 18. The floating car experienced the highest level of congestion between stations 45–47 where it averaged a speed of 10.79 km/hr over a distance of 1.27 km. Between these two detectors are busy freeway on and off ramps which may increase to the vehicle delay. The floating car traveled between these stations during the time of 8:13:37–8:21:42. The speed of vehicles during the same period as indicated from the loop detector data over station 45 was 16 km/hr and 52 km/hr over station 47. This could be indication that heavy congestion is existent at station 45 because it is just downstream of a lane drop in the freeway.

### C. Variable Speed Sign Data

A variable speed limit (VSL) system uses real time data provided via inductive loops, closed circuit television (CCTV), remote weather information systems (RWIS), or observational data to evaluate the existing traffic and or weather conditions in order to determine a recommended speed along a particular roadway segment. The recommended speed is typically indicated to vehicle drivers using variable message signs (VMS) located along the roadway or overhead. Currently, VSL is implemented on this section of A9.

In several European countries this practice has been implemented in order to reduce crashes, reduce congestion, and increase flow during peak periods. This practice has been successful and research is being conducted to determine whether deployment on U.S. freeways should be considered. In order to do this, an understanding of when speed limits should be reduced/increased and by how much must be known. The effects (increased flow, safety, and driver compliance) of the speed change on the road network must also be known to determine system benefits.

Variable speed limit data from the 10 dynamic message signs on southbound A9 on May 21, 2003 were provided. The data consisted of the speed limit posted on each sign throughout the day as well as any driver information such as warnings or prohibitions posted on the sign. Speeds posted on the sign ranged from 60–120 km/hr between 5:30–11:00.

Fig. 9 displays the speed contour map of the variable speed limits between 5:30–11:00. During this period, four designated speeds were posted (120, 100, 80, and 60 km/hr). The dark shaded areas represent 120 km/hr, the lighter shade of black indicates 100 km/hr, the dark grey 80 km/hr, the light grey 60 km/hr, and the white no speed limit was posted or a communication failure occurred. At 6:00, variable message signs AQ 204, AQ 206, and AQ 208 posted 100 km/hr. Sign AQ 210 posted 80 km/hr while sign AQ 212 posted 60 km/hr at this time. The remaining message signs downstream of AQ 212 had no speed posted at this time. Interestingly AQ 212 is located just downstream from station 43 which had a speed limit of 60 km/hr posted beginning at 5:37 and remaining posted until 6:12 when it began fluctuating between no speed posted and a posted speed of 60 km/hr. As suspected, this could be the indication of why speeds were lower downstream of station 45. Looking at Fig. 2, it is noticeable that speeds were much greater than that indicated on the variable message sign. Between 5:37–7:56 the word “congestion” was displayed on AQ 212. AQ 213 had no posted speed, but displayed the
“congestion” between 5:37–6:31 prior to bottleneck activation. The same was posted for AQ 214 between 5:04–8:01 and for AQ 215a from 4:59–7:56. Prior to bottleneck activation no speed was posted on the three upstream most message signs.

D. Weather Data

Weather data for the day of May 21, 2003 indicated no extremes in weather [11]. The mean temperature was 10ºC with mostly cloudy conditions. No precipitation was recorded and average wind speeds were 13 km/hr. During the time of bottleneck activation, the skies were recorded as clear and visibility at 10 km. There are no indications that weather conditions had any impact on driver behavior and the activation of the bottleneck between stations 53–57.

V. CONCLUSION

Using historical inductive loop detector data from May 21, 2003 on the southbound section of Autobahn 9, speed contour plots were constructed to determine areas of slow speeds. A potential bottleneck was identified between stations 53–57 that became active at approximately 6:15 and remained active until approximately 10:00. This was confirmed through the use of transformed cumulative plots of vehicle arrival versus time and time-average velocity versus time. These plots both confirmed a decrease in speed and an increase in flow between these two stations. These plots indicated a relatively high speed of above 90 km/hr and a relatively flow over station 57 which indicated freely flowing conditions at this station.

This location was between an on- and off-ramp. Investigation into the estimated flows of vehicles entering and exiting the freeway before the bottleneck activation at approximately 6:30 confirmed an increase in vehicles at both ramps at approximately 6:15. A surge in flow entering and exiting the freeway may have triggered the bottleneck’s activation with a large number of vehicles changing lanes. The percentage of vehicles traveling in the median travel also increased before the bottlenecks activation. This may indicate that trucks were merging into the left lane due to the large number of vehicles entering and exiting the freeway. The trucks in the median lane may be restricting vehicular flow that may otherwise be greater.

Variable message sign data was found to be relatively consistent with estimating congestion on the freeway. Estimated congestion parameters were presented to drivers in advance by the use of overhead dynamic message signs. The congestion parameters were presented to drivers in terms of length of congestion rounded to the nearest km. Analysis concluded that the messages were presented to drivers in advance of the estimated congestion and that the parameters matched fairly well with those indicated by the speed contour plots. The parameters were shifted to the right, which may indicate that the messages were based on previously recorded detector data.

Floating car data provided microscopic details of speed as is traveled through congested conditions and the active bottleneck between stations 57–53. The congestion existed between 6:30–10:00 added an additional 0:16:17 of travel time as compared to the floating car that experience near-free-flow conditions. The trajectory of the floating car was placed over the speed contour plot and found to be consistent. Analysis of travel time based on the loop detectors and floating car was conducted and found that large variances were existent. A more detailed analysis will be conducted.

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REFERENCES