A Study of the Response of Highway Traffic to Dynamic Fog Warning and Speed Advisory Messages

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Abstract. This study examines the response of traffic to messages displayed by a changeable message sign (CMS) warning of fog ahead and advising specific speeds at progressively lower visibility levels. Over a two-year period of study, the speed, length and time of detection were individually recorded for all vehicles at four sites: two prior to exposure to the CMS, and two after exposure to the CMS. We calculated mean speed, speed variance and a new metric, potential collision speed (PCS), using a 45 second moving window as well as averaged over each constant-message state. PCS is a predictor of the impact speed in a potential chain collision that considers visibility as well as the speed and separation between individual vehicles.

Over all fog events in which the CMS was activated, mean speed decreased an average of 1.1 mph compared with the mean speed of traffic in the absence of a message. However, average PCS increased differentially by 8 mph, due to compression of platoons and the sensitivity of this metric to progressively worse visibility after the CMS during most activations. Speed standard deviation among proximate vehicles did not appear to be significantly effected, staying within of 5-7 mph across all lanes in most cases. The warning messages were found to evoke a measurable effect on driver behavior, but well below design expectations. Drivers appeared to respond predominantly to their own perceptions and reduced speed in fog, but not nearly enough to compensate for the reduced visibility distance. When advised to reduce speed to 30 mph in dense fog, mean speeds averaged 61 mph.

BACKGROUND

There is considerable interest in methods to mitigate the enhanced risk to drivers on highways during periods of low visibility due to fog. Among the most topical are enhanced driver information systems which provide advanced warning of fog or traffic disturbances, and sometimes advise appropriate speeds. According to the National Highway Transportation Safety Administration (NHTSA) Fatality Analysis Reporting System (FARS), visibility-impairing fog was present and presumed a factor in 418 of the 38,309 fatal crashes that occurred nationwide (USA) in 2002 (1). Although fog crashes account for only a small percentage of all crashes, they often involve multiple vehicles and massive losses, not revealed by the raw statistics. Fog is a transient phenomena, difficult to predict and variable in density, location, dissipation rates, and area. Among the many publications on this topic, National Cooperative Highway Research Program Synthesis reports in 1976 (2), 1991 (3) and 1996 (4) have addressed many of the issues related to highway fog and potential means for mitigation of the hazard.

One of the earliest automated fog warning systems was developed as part of the Drive II project, the Roadway Safety Enhancement System deployed on the A16 near Breda in the Netherlands in 1992 and evaluated over a two year period 1992-94 (5). Several manually and automatically actuated systems have been deployed in the US.
including Arizona (6), Idaho (7), North Carolina (8), Georgia (9,10), Oregon (11,12,13), Virginia (14), Tennessee (15,16), Florida (planned) (17,18), California (19,20,21,22) and Utah (23,24). In Europe, in addition to the Dutch system, automated and semi-automated driver warning systems have been deployed in Finland (25,28), Germany (28), Australia (28), and England (26). Real-time variable speed limits have been implemented in Britain, Germany and the Netherlands for many years (27,28).

Our study of driver response was part of the evaluation of the Caltrans Automated Warning System (CAWS), a fully-automated fog and traffic warning system located on a 15 mile stretch of Interstate 5 and State Route 120 in California’s Central Valley. This valley is known for seasonal Tule fog occurring from approximately October through April, and has historically been prone to multi-car accidents due to fog. Interstate 5 is the major north-south traffic artery that runs the length of this corridor. The CAWS and the methods used for its evaluation were described in (29) and (30). The CAWS consists of a network of nine remote meteorological stations including visibility sensors, 35 traffic speed monitoring stations, and nine self-illuminated changeable message signs (CMS) deployed over approximately fifteen miles of I-5 and SR-120. It first became operational in November 1996 and remains in operation at the time of this publication.

The behavioral response of drivers to traffic management interventions of all types has been the topic of research for many years, for example (17,31,32,33). Exposure of drivers to an appropriate warning message during foggy conditions increases the time available for reaction and provides drivers with information on hazards beyond their visual range, such as a traffic slowdown or stoppage ahead. Conformance to a reduced speed is the usual objective of warning interventions, but the actual effects on driver behavior and traffic safety are not well-documented, and may be situation-specific.

In 1964 (34), the FHWA studied a large sample of accidents on rural highways and observed that vehicle speed and crash incidence were related by a U-shaped curve, with the minimum accident rate occurring near the mean traffic speed. In 1989 Garber and Gadiraju (35) found that the difference between the highway design speed and the posted speed limit has a statistically significant effect on the speed variance, and that accident rates increase with increasing speed variance. They also concluded that the accident rate on a highway does not necessarily increase with an increase in average speed. An FHWA Synthesis 2002 (36) addressed the role of traffic speed on traffic safety. It concluded that collision risk was not a monotone increasing function of speed, but more a function of the difference of the vehicle speed above or below the mean traffic speed, and that accident rates tend to increase with the difference between the 85th percentile or the mean traffic speed and the posted speed limit. The synthesis also concluded, based on data from several other studies, that drivers travel at speeds they feel are reasonable and safe for the road and traffic conditions, regardless of the posted speed limit. This observations were particularly apropos to our study, since they address the possibility of affecting driver behavior with dynamic speed advisory messages.

As early as 1967, it was reported that in poor visibility, mean and 85th percentile speeds usually decreased by 5-8 mph, but that some drivers continue at speeds higher than the posted speed limit (37). More recently, Hogema and van der Horst (32) observed that drivers naturally reduce their speed in fog, but that speeds were excessive for the visibility-limited sight distance. These authors (38,39) evaluated the effect of visibility-dependent variable speed limits as part of the active warning system on the A16 in the Netherlands 1992-94. They reported a systematic average reduction of mean speed of 8-10 km/h (5-6 mph) at sites which benefited from dynamic (lane-specific) speed warning messages, although headway, following distance, and Time-To-Collision were not significantly affected.

In a study of the effects of a Variable Message Sign (VMS) at a bridge in an area of recurrent fog, Martin et. al. (40) used as metrics of safety the mean, standard deviation, skewness and kurtosis of the speed distribution. Comparisons were made during winters before and after the VMS was in operation, and during the periods immediately before, during and after a warning message was displayed. They reported a decrease in speed variation of 22% but an 8 mph increase in the mean speed measured while the message was displayed.

**EVALUATION METHODOLOGY**

We non-intrusively monitored traffic before and after drivers were exposed to the first CMS encountered upon entering the CAWS area on I-5. Two monitoring stations were located on the roadway before drivers encountered the first CMS. These stations are located 0.8 and 0.7 miles respectively from a slight rise in the roadway which
blocks the view of the CMS from approaching drivers. The CMS is located 0.5 miles after this high point and is only visible in this interval. Two monitoring stations were located immediately after drivers have encountered the CMS, at 0.5 and 1.1 miles after the CMS respectively.

All stations collected individual records of the time of arrival, speed and length of every vehicle in each of the three lanes at each site. Duplex inductive loop detectors were used in each lane to detect the time of arrival (to 0.01 second) and speed (to 0.1 mph) of each vehicle. Forward dispersion visibility sensors monitored local visibility at each of the inner-most before and after sites. Video cameras were deployed before, at, and after the CMS for verification of conditions. The message displayed by the CMS was monitored by direct interception of communications, and verified by a video camera. Data were transmitted and verified over wireless connections to a central server, which also hosted a real-time web site http://caws-evaluation.loragen.com which provided public access to data. A diagram of the monitoring stations before and after the CMS is shown in Figure 1. Figure 2 is a sample image of the CMS acquired by the verification camera.

The CMS is actuated solely by the Mathews Road Weather Station (WS1), which is the same as our first After-CMS monitoring site. During the first complete fog season (Nov. 2003- Apr 2004), the CMS displayed two pre-programmed messages: “DENSE FOG AHEAD, ADVISE 45 MPH” when fog-visibility was between 200 and 500 ft., and “DENSE FOG AHEAD, ADVISE 30 MPH” when fog-visibility was between 100 and 200 ft. When fog-visibility dropped below 100 ft., no message was displayed. During the second complete fog season (Nov. 2004- Apr 2005), the CAWS displayed a single warning message for all fog visibilities less than 500 ft.: “DENSE FOG AHEAD, ADVISE 45 MPH”. Only fog-related visibility is recognized; no message is displayed if relative humidity is less than 75% regardless of the visibility reading.

From the raw data, we calculated mean speed, speed variance (measured as sample standard deviation), and potential collision speed for all vehicles detected within a 45-second moving window, incremented every 15 seconds. This approach facilitated real-time measurements of each metric based on a small set of vehicles proximate in both time and position on the roadway. When restricted to such a short period, speed variance differs from variance measured over an entire event in that it considers only interactions between vehicles whose movements can potentially affect each other. The narrow time window also permits the observation of rapid transients, for example, immediately following the activation of a CMS message. However, the small number of vehicles accumulated makes these measurements can be prone to sample noise during light traffic.

Potential collision speed (PCS) may be interpreted as the predicted impact speed if the vehicle encounters an obstruction on the highway (as in a chain collision in fog). It is used as a means to factor in both the visibility sight distance and the following distance between successive vehicles at a given speed, providing a progressive indication of comparative danger for each vehicle in the event of a traffic disturbance. The relationship between the projected impact velocity and the separation distance or the visibility sight distance is given by equation [1] below. The driver reaction time \( t_{react} \) was assumed to be 0.75 second and coefficient of friction 0.5 (41).

\[
\begin{align*}
    v_{impact,i} &= \begin{cases}
        v_{0,i} \sqrt{1 - \frac{\min\{x_{vis}, x_{gap,i}\} - x_{react,i}}{x_{brake,i}}} , & \min\{x_{vis}, x_{gap,i}\} \geq x_{react,i} \\
        v_{0,i} , & \min\{x_{vis}, x_{gap,i}\} < x_{react,i}
    \end{cases} \\
    x_{vis} &= \text{initial velocity of following vehicle} \\
    x_{vis} &= \text{visibility site distance} \\
    x_{react,i} &= t_{react} v_{0,i} = \text{reaction distance of vehicle } i , \quad t_{react} = \text{driver reaction time} \\
    x_{gap,i} &= (t_{0,i} - t_{0,i-1}) v_{0,i-1} = \text{separation between vehicle } i \text{ and } i-1 \\
    t_{0,i} \text{ and } t_{0,i-1} \text{ are the detection times for each vehicle} \\
    x_{brake,i} &= \frac{v_{0,i}^2}{2gk_{friction}} = \text{braking distance of vehicle } i
\end{align*}
\]
This relationship is plotted in Figure 3. Its range extends from 0 mph, which means the vehicle could safely brake to a stop, to a maximum equal to the vehicle speed, which means the vehicle would impact the obstruction before even starting to brake, or equivalently, it could not avoid collision with a vehicle in front of it even if that vehicle braked normally to a stop. Such a metric was appropriate for this study since 68.8% of collisions that occurred in fog in the study area from January 1997 to December 2003 were classified by the California Highway Patrol as “rear end” or “hit object” collisions (42).

OBSERVATIONS AND RESULTS

Time-history of fog events

Figure 4 presents data from the first two hours of a typical CMS activation due to fog, on January 8, 2004 at 22:00 (10:00 PM). The complete event lasted until 06:15 the following morning.

The abscissa is clock time in 24-hour format. BCMS = ‘Before the CMS’. ACMS = ‘After the CMS’. Readings are reported as the average of the two BCMS and the two ACMS sites, respectively. Centered 45-second moving averages are used to establish trend lines through the data cloud (individual points are suppressed for clarity) for PCS and mean speed on the lower part of the plot. Since speed standard deviation did not vary significantly between the sites, it is not plotted. Visibility is reported on the upper part of the plot as an extinction coefficient measured at the BCMS (in green) and ACMS (in purple) sites, with an equivalent visibility distance scale on the left. Dashed lines indicate the visibility thresholds for CMS messages at 500, 200 and 100 feet. The state of the warning messages are shown at the top. For mean speed and PCS, BCMS measurements are in red and ACMS measurements are in blue. For alignment purposes, note that vehicles detected at the BCMS sites are detected at the ACMS sites approximately two minutes later, depending on their individual speeds. The CMS is controlled by the visibility sensor at the first ACMS site.

This event was characterized by a quickly moving fog front. Visibility started to degrade at 22:17. A response lag of approximately 5 minutes can be seen between the time the visibility fell below 500 feet at 22:27 and the CMS message appeared at 22:32. Overall, an average a response lag of 7 minutes has been observed, attributed to multiple polling cycles used by the CAWS to first read the field sensors and then actuate the appropriate CMS(s). Visibility remained very poor and was consistently worse ACMS than BCMS. Mean speeds did not measurably change at the ACMS sites until almost 22:43, when visibility fell below 100 feet, 10 minutes after the CMS message. ACMS speeds reduced to approximately 3 mph lower than BCMS from 22:45 on, even while the CMS was blank during 20:53-23:13, 23:17-23:40, and 23:52-23:55 when visibility dropped below 100 feet.

Examination of the event history reveals that drivers decreased speed from approximately 70 to 60 mph as they entered the fog bank, although mean speed remained above 60 mph even during visibility below 100 ft. PCS at the ACMS sites increased from initially 10-20 mph to nearly the same as the mean speed as visibility became worse. Focusing on the points of message transitions, the presence or non-presence of either level of CMS message showed only a small influence, possibly enhancing the speed reduction.

Dependency on visibility

Figure 5 is a plot of the speed recorded at each of the four sites related to visibility. Approximately 118 million vehicle detections are represented by this plot. The densely-plotted points that appear to be lines are the result of a moving visibility-window average over the data set. A ± 1% window for the extinction coefficient (inversely related to visibility distance) was used, and the speeds of all vehicles detected within that range of visibility were averaged. The two BCMS sites (numbered 4 and 1) are coded red and yellow, and the two ACMS sites (numbered 2 and 5) are coded green and blue. The vertical dashed line marks the 500 foot visibility threshold, below which the CMS would display a message that presumably could influence drivers at the two ACMS sites (2 and 5).

Since the two BCMS sites are only 0.1 miles apart, data from each are nearly identical. The two ACMS sites are 0.6 miles apart, so a slightly larger data spread between them can be seen. For all visibility distances above 800 feet, the mean traffic speed was reasonably constant at 69.0 mph BCMS and 70.2 mph ACMS. Below this, drivers at all sites naturally decrease speed, showing the same declination rate with speed until visibility falls below 150 feet, below which the speeds BCMS become significantly slower than ACMS. However, this narrow range of visibility (100 to
150 ft) is prominent because of the logarithmic visibility scale, and is probably not significant. ACMS and BCMS comparisons of mean speeds for visibilities between 150 and 500 feet show no evidence of a supplemental speed-reducing influence of the CMS message.

Figure 6 and Figure 7 lead to similar conclusions for proximate standard deviation of speed and potential collision speed, respectively. In Figure 7, the upward inflection of PCS for visibilities below 600 feet at both sites is notable. It probably represents an actual misjudgment of safe following distance by drivers, and cannot be attributed to the transition from separation distance to visibility distance as the limiting factor in the PCS calculation until below 300 feet. There is no significant evidence that PCS or speed variance in fog is influenced by the presence or non-presence of speed advisory messages.

Cumulative results for constant message periods

Table 1 examines the difference between the BCMS and ACMS sites during periods in which a particular message was displayed. This table pertains only to the first year of the study, during which both 30 and 45 mph advisories were enabled. Blank message periods were limited to two hours before and after each fog event to assure consistent road conditions. In this table:

- **Message Type** is the message displayed (30 mph, 45 mph or blank).
- **Count** is the total number of individual times the message was displayed.
- **Total Duration** is the total time in seconds that the message was displayed.
- **Mean Spd** is the difference between the mean speed ACMS and BCMS, measured over the duration of the message period (mph).
- **Spd STD** is the difference between the speed standard deviation ACMS and BCMS, measured over the duration of the message period (mph).
- **PCS** is the difference between the mean PCS ACMS and BCMS, measured over the duration of the message period.
- **Event Average** is the average of the numbers generated for each instance that the message was displayed, one value per display period.
- **Time-Weighted** is the time-cumulative average or standard deviation measured over all periods that the message was displayed.
- **% Events Values Decreased** is the percentage of the display periods in which the value of the metric measured ACMS was less that the value BCMS. For all metrics, larger percentages indicate safer traffic ACMS compared with BCMS.

Consider first part (a) of Table 1. The ADVISE 45 MPH message was displayed a total of 86 times over a total duration of 106,006 seconds.

Mean speed decreased an average of 0.60 mph ACMS compared with BCMS, when cumulatively time averaged. The natural response of drivers, revealed when the message is blank, is a 1.42 mph increase in traffic speed ACMS compared with BCMS. Mean speed decreased ACMS 61.63% of the times that the message was displayed. This is an indication that the display of this message affects a reduction of 2.0 mph relative to the natural tendency of the drivers to speed up at the ACMS sites.

Speed standard deviation (Spd STD) decreased a time-averaged difference of 0.09 mph ACMS compared with BCMS. But when no message was displayed, this metric decreased by 0.13 mph. If these small differences were significant, they would indicate that variance of speeds naturally reduced ACMS more than with the added influence of this message. The fact that Spd STD decreased only 53.5% of the time confirms the nearly neutral relationship.

PCS increased by 10.17 mph during the warning messages, compared with 0.36 mph when no message was displayed, a net gain of 9.8 mph. PCS decreased only 16.28% of the times this message was displayed. It appears that the positive effect this message may have had on mean speed was at least balanced by a negative effect on PCS.
Similar observations can be made for the 47 times and 63203 seconds that the 30 mph advisory message was displayed, affecting a somewhat greater 2.8 mph mean speed reduction relative to the blank message response, but a dramatically greater 20.6 mph increase in PCS.

For the nine cases in which no message was displayed due to visibility below 100 ft., drivers reduced their speed more than when the 45 mph message was displayed, but less than when the 30 mph message was displayed. PCS was slightly higher than either of the latter cases. This seems to confirm that drivers were responding primarily to the reduced visibility, although the warning message may have supplemented their response.

During most periods, visibility BCMS and ACMS were significantly different, most often with visibility worse ACMS since this site controlled the CMS. Parts (b),(c), and (d) of Table 1 are presented in recognition of the dependency of the results on local visibility. Part (b) confirms that drivers slowed down when driving into denser fog as they traveled from BCMS to ACMS, but Part (c) shows that when visibility improved ACMS compared to BCMS, drivers increased their speed despite the speed advisory messages. In the few cases (Part d) that visibility was approximately equal before and after the CMS displaying a 45 advisory, the cumulative time-averaged incremental speed change relative to the blank message was -0.18 mph, and the PCS change was -3.53 mph, suggesting a small positive influence of the message.

**Cumulative response segregated by fog or non-fog**

Table 2 presents composite results over all periods during which fog was present or not present at each of the four sites. A breakdown by lane is included to possibly reveal lane-specific behaviors. Observation of speed STD on an individual lanes basis also helps to remove the normal effects of different lane speeds. Lane 3 is used primarily by trucks with speed limit 55 mph, while lane 1 is used exclusively by cars and light trucks, with speed limit 70 mph.

This view of the data shows, in the most consolidated way, the response of drivers in fog at the ACMS vs. the BCMS sites. Sites 4 and 1 are the BCMS sites, and Sites 2 and 5 are the ACMS sites. We restricted the data to the periods extending from two hours before to two hours after CMS activation events. This reduced the total number of detections considered in the table from 118 million to 3.5 million over the two-year period.

Considering all lanes during fog vs. non-fog conditions, mean speed decreased 3.3 mph BCMS and 4.4 mph ACMS, a difference of 1.1 mph that is attributed to the incremental effect of the CMS messages. On average, PCS increased 5.1 mph BCMS and 13.1 mph ACMS, a difference of 8.0 mph. The greatest effect on speed was in lane 2 (-1.43 mph), and least effect was in lane 3 (-0.58 mph). The greatest increase in PCS occurred in lane 3 (+15.41 mph), followed by lane 2 (+7.35) and lane 1 (3.52).

For the ACMS sites in fog, the average difference between the mean speed in lane 1 and the mean speed in lane 3 was 10.9 mph. At the BCMS sites, the average difference was 11.2 mph. For comparison, under non-fog conditions, these values were 11.8 ACMS and 11.7 BCMS. In non-fog conditions, essentially no change in inter-lane speed spread is observed ACMS vs. BCMS. But in fog, inter-lane speed spread is reduced 0.3 mph more at the ACMS sites than at the BCMS sites, suggesting a small positive effect on lane-to-lane speed differences.

**CONCLUSIONS**

When plotted as a function of visibility, there is little to no evidence that mean speed, speed standard deviation or PCS were influenced by the CMS messages. The exception may be for visibilities between 100 and 150 feet, during which all three metrics increased slightly after drivers viewed the CMS. However, it must be noted that the system response delay, typically 7 minutes, misaligned the display of the warning message from the actual visibility conditions, which reduced the reliability of the relationship between visibility and traffic characteristics.

To avoid this limitation, we examined the metrics in a number of comparative ways during periods in which a CMS message was correctly displayed. This yielded evidence that the speed advisory messages may slightly enhance the natural tendency of drivers to reduce mean speed and increase PCS as visibility decreases. Overall, the messages appeared to be responsible for an average incremental speed reduction of 1.1 mph and an average increase in PCS of 8.0 mph. Speed standard deviation was not significantly influenced by visibility or the state of the CMS, staying within the range of 5-7 mph during most events. For the rare conditions of nearly equal visibility before and after
the CMS while a fog message was displayed, we observed a mean speed decrease of 0.36 mph and an insignificant change in PCS.

The mean speed reduction suggests increased safety, while the increase in PCS suggests decreased safety, overall a neutral result. Two phenomena explain this apparent paradox: Since PCS depends on the minimum of the following distance and the visibility distance, it increases when widely separated vehicles in fog experience a decreasing visibility gradient. In sparse traffic, PCS usually increases because visibility is more often worse ACMS than BCMS. In more dense traffic, PCS increases apparently because a minority of drivers heed the speed advisory message and reduce their speeds slightly. This reaction leads to more densely packed platoons as the majority of drivers, who ignore the CMS message, accumulate behind the conforming drivers and reduce their separation distance to less safe levels for the given speed and visibility.

During fog events, drivers continue at mean speeds consistently above 60 mph, even in visibilities below 100 ft. Mean speeds in visibility as poor as 700 feet do not vary from speeds under clear conditions, typically 69-71 mph over all lanes, and 74-76 mph in lane 1. In fog, PCS values between 45 and 60 mph are typical, while averaging 20-30 mph during clear conditions. Drivers appear to predominantly make their own decisions about safe speed and separation distances for the visibility and traffic conditions. A much more substantial decrease in both mean speed and PCS must be achieved if a significant reduction in the risk and severity of chain collisions is to be achieved.

ACKNOWLEDGEMENTS AND DISCLAIMER

This work was funded by the California Office of Traffic Safety and administered by the California Department of Transportation, Division of Research and Innovation. The Caltrans project monitor was Andrew Lee, whose support has been critical to the performance of the evaluation. Special thanks to Clint Gregory and Veronica Cipponeri of Caltrans District 10 for their support of our evaluation efforts. Unless specifically attributed, all statements and opinions expressed herein are the responsibility of the authors, and do not reflect the official views or policies of Caltrans, the Office of Traffic Safety, or the State of California.

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42. Traffic Accident Surveillance and Analysis System (TASAS) Table B. The TASAS database is operated by the California Department of Transportation and the California Highway Patrol. Information online at http://www.dot.ca.gov/hq/traffops/signtech/signdel/chp3/chap3.htm#3-04.
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Table 1. Cumulative results for periods in which each message type was displayed.

(a) All cases

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<th>Tot Dur</th>
<th>Event Avg</th>
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<td>Mean Spd</td>
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(b) Visibility worse ACMS

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(c) Visibility worse BCMS

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<td>3210</td>
<td>2.89</td>
<td>-0.15</td>
<td>-2.67</td>
</tr>
<tr>
<td>Fog 30 MPH</td>
<td>1</td>
<td>717</td>
<td>1.69</td>
<td>-0.93</td>
<td>9.19</td>
</tr>
<tr>
<td>Blank with &lt; 100ft Vis</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Blank</td>
<td>7</td>
<td>46632</td>
<td>1.73</td>
<td>-0.01</td>
<td>-1.52</td>
</tr>
</tbody>
</table>

(d) Visibility same at both sites

<table>
<thead>
<tr>
<th>Event Type</th>
<th>Count</th>
<th>Tot Dur</th>
<th>Event Avg</th>
<th>Time Weighted Average</th>
<th>% Events Values Decreased</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Mean Spd</td>
<td>Spd STD</td>
<td>PCS</td>
</tr>
<tr>
<td>Fog 45 MPH</td>
<td>2</td>
<td>2506</td>
<td>2.36</td>
<td>0.48</td>
<td>-1.67</td>
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<tr>
<td>Fog 30 MPH</td>
<td>2</td>
<td>1439</td>
<td>0.69</td>
<td>1.03</td>
<td>14.06</td>
</tr>
<tr>
<td>Blank with &lt; 100ft Vis</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Blank</td>
<td>4</td>
<td>28800</td>
<td>1.79</td>
<td>0.11</td>
<td>0.91</td>
</tr>
</tbody>
</table>
Table 2. Cumulative results discriminated by fog or no-fog periods at each site. Fog is defined as visibility less than 500 feet.

<table>
<thead>
<tr>
<th>Site 4 (BCMS)</th>
<th>No Fog</th>
<th>Fog</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Mean Speed</td>
<td>Speed STD</td>
</tr>
<tr>
<td>All Lanes</td>
<td>68.66</td>
<td>7.45</td>
</tr>
<tr>
<td>Lane 1</td>
<td>73.84</td>
<td>5.16</td>
</tr>
<tr>
<td>Lane 2</td>
<td>68.37</td>
<td>6.08</td>
</tr>
<tr>
<td>Lane 3</td>
<td>62.39</td>
<td>6.41</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Site 1 (BCMS)</th>
<th>No Fog</th>
<th>Fog</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Mean Speed</td>
<td>Speed STD</td>
</tr>
<tr>
<td>All Lanes</td>
<td>68.44</td>
<td>7.3</td>
</tr>
<tr>
<td>Lane 1</td>
<td>73.99</td>
<td>5.17</td>
</tr>
<tr>
<td>Lane 2</td>
<td>67.89</td>
<td>5.23</td>
</tr>
<tr>
<td>Lane 3</td>
<td>62.14</td>
<td>6.32</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Site 2 (ACMS)</th>
<th>No Fog</th>
<th>Fog</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Mean Speed</td>
<td>Speed STD</td>
</tr>
<tr>
<td>All Lanes</td>
<td>70.58</td>
<td>7.25</td>
</tr>
<tr>
<td>Lane 1</td>
<td>75.42</td>
<td>5.1</td>
</tr>
<tr>
<td>Lane 2</td>
<td>69.04</td>
<td>5.67</td>
</tr>
<tr>
<td>Lane 3</td>
<td>63.72</td>
<td>6.79</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Site 5 (ACMS)</th>
<th>No Fog</th>
<th>Fog</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Mean Speed</td>
<td>Speed STD</td>
</tr>
<tr>
<td>All Lanes</td>
<td>70.66</td>
<td>7.13</td>
</tr>
<tr>
<td>Lane 1</td>
<td>75.14</td>
<td>4.61</td>
</tr>
<tr>
<td>Lane 2</td>
<td>70.06</td>
<td>5.64</td>
</tr>
<tr>
<td>Lane 3</td>
<td>63.33</td>
<td>6.91</td>
</tr>
</tbody>
</table>
Figure 1. Monitoring sites on I-5 (distances not to scale).
Figure 2. Image of CMS 1 from verification video camera.
Figure 3. Potential collision speed (impact velocity) v.s. the minimum of the following distance or visibility distance. Curve is parametric with initial speed $v_0$. 

$v = \text{vehicle speed (ft/sec or m/s)}$

$v_0 = \text{vehicle speed prior to braking}$

$x = \text{distance traveled (ft. or meters)}$

$\min\{x_{\text{vis}}, x_{\text{following}}\}$

$\Delta x_{\text{react}} \quad \Delta x_{\text{brake}}$
Figure 4. Mean speed and potential collision speed (PCS) before the CMS (BCMS) and after the CMS (ACMS) during a dense fog event.
Figure 5. Mean speed related to visibility by site. All lanes, all hours, two years.
Figure 6. Speed standard deviation related to visibility by site. All lanes, all hours, two years.
Figure 7. Potential Collision Speed (PCS) related to visibility by site. All lanes, all hours, two years.