Speed Pattern Analysis in the Proximity of Dynamic Message Signs Using a Driving Simulator

Brittany A. Spell
Research Assistant
Department of Transportation and Urban Infrastructure Studies
Morgan State University
1700 E. Cold Spring Lane, Baltimore, MD 21251, USA
Phone: (443)885-4734
Fax: (443)885-8324
Email: brspe1@morgan.edu

Anam Ardeshiri
Doctorate Candidate
Department of Transportation and Urban Infrastructure Studies
Morgan State University
1700 E. Cold Spring Lane, Baltimore, MD 21251, USA
Phone: (443)885-4734
Fax: (443)885-8324
Email: anard1@morgan.edu

Mansoureh Jeihani *
Associate Professor
Department of Transportation and Urban Infrastructure Studies
Morgan State University
1700 E. Cold Spring Lane, Baltimore, MD 21251, USA
Phone: (443)885-1873
Fax: (443)885-8324
Email: mansoureh.jeihani@morgan.edu

* Corresponding Author

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ABSTRACT

This study aims to find whether dynamic message signs (DMS) have an adverse effect on traffic flow and safety due to traffic slowdown to read the message. Drivers’ speed fluctuations in the proximity of two dynamic message signs with qualitative and quantitative contents on a highway and a freeway are analyzed. Over 100 subjects are recruited to drive on a fairly large and realistic road network developed in a driving simulator. No statistically significant reduction in the speed of the subjects to read the quantitative message in a highway with 55 mph (88.5 km/hr) speed limit was found. In correlation with our speed analysis, majority of the subjects believed their speed reduction was insignificant. However, the average speed decreased by 2.6 mph (4.3 km/hr) to read the quantitative message on a sign mounted on the 65 mph (105 km/hr) freeway. Although DMS accounted to likely impact the speed of fast drivers, they were found to safely operate as traffic management tools.

Keywords: Dynamic Message Sign, Speed limit, Driving simulator, Drivers’ behavior.
BACKGROUND

Dynamic message sign (DMS), sometimes referred as variable message sign (VMS) or changeable message sign (CMS), are used along primary highways and their connecting roadways to communicate travel information to motorists. DMSs convey real-time information to travelers on traffic congestion, roadway hazards, weather conditions, AMBER alerts, and other regulatory messages. As a component of intelligent transportation systems, integrating this technology allows users to make informed travel choices, helping to improve mobility, productivity, throughput, safety, and traveler satisfaction. While DMSs are intended to provide such benefits, some argue that DMS may cause distractions and speed reductions, which may increase crash risks. It has also been observed that after a slowdown to read a DMS, motorists increased their speed upon passing the DMS to account for speed loss during the slowdown (1).

Some DMS messages are displayed in more than one phase to convey a longer message. Using a survey questionnaire, Wang et al. (2) concluded that lengthy messages, abbreviated messages, and complex wording on DMS are principle reasons for traffic slowdowns. Dutta et al. (3) concluded that with no obstruction, repeating a message had no statistically significant effect on route choice behavior compared to non-repeating messages. The display time is an important factor to allow drivers to read the DMS. The New York State thruway authority guidelines (4) emphasized that the exposure time must be equal or greater than the message display time, where it depended on the highway speed. The guidelines, which adhered to the Manual on Uniform Traffic Control Devices (MUTCD) (5), recommended that the sign placement maintain at least a 2,640-ft (800-m) visible area and a 650-ft (200-m) legible area for 18-inch (46-cm) character height. The Oregon Department of Transportation (6) necessitated allowing drivers to read DMS twice. For instance, 3 seconds is needed to read a 3-line message twice at 55 mph (88.5 km/hr) speed.

Field speed data has been conventionally collected in relevant studies to analyze the impact of a DMS on traffic flow. Wang et al. (2) utilized mobility technology units to calculate vehicles’ speed approaching three types of messages displayed on DMS; danger warning, informative, and regulatory. The study collected the average speed of vehicles in four 5-minute intervals, “pre-display,” “first 5-min,” “last 5 min,” and “post-display.” In a before-and-during analysis, the study compared the first two 5-minute intervals. Using t-test at 0.1 significance level, speed reduction was reported in ten of the sixteen cases, while only four were statistically significant. Supplementary analysis of the second pair of 5-minute intervals demonstrated that speed increases occurred in seven of the sixteen cases, only two of them being statistically significant. However, the study’s survey results indicated that 90 percent of the drivers would always or sometimes slow down when approaching an active DMS. There was no significant evidence of speed change when DMS was off, likely due to drivers’ route familiarity.

Haghani et al. (7) conducted a speed analysis on consecutive 5 minute periods for “off-on” operations of DMS. Data was collected using remote traffic monitoring sensors that were mounted forward the DMS placement. Using t-test at 95 percent confidence level, speed reduction occurred only in 17 percent of cases, and speeds increased or were unaffected in the remaining 83 percent. However, the study found an average of 3.1 mph (5 km/hr) speed reduction for all types of active DMS versus inactive ones; overall suggesting that DMS is not likely to cause traffic congestion or to adversely affect traffic safety. The study also found no clear indication that traffic slowdown for DMSs with quantitative travel time information is significantly different from DMSs displaying other types of messages. Erke et al. (8) measured the speed of 1,532 vehicles approaching an active DMS and 1,810 vehicles approaching an
inactive DMS, the latter as a control group, in two sites. The study found a large speed reduction (6 and 4.7 km/hr in each sites) which was partly attributed to the message contents on the DMS; however, a subsequent brake analysis revealed that a high proportion of the speed reduction was due to chain reaction effect.

Transportation researchers have been using the evolving driving simulator (DS) technology to investigate drivers’ controlled behavior for various conditions. Harder et al. (9) used a PC-based DS to evaluate speed slowdowns when drivers approached a DMS. Speed was collected in four segments before approaching the sign, each approximately 1000 ft (300 m). The study concluded that 17.5 percent of the participants slowed down by at least 2 mph, when approaching a sign. The study also concluded that the likelihood of slowdowns impact on traffic flow depended on density conditions and the degree of the slowdowns. The major debate in this context is the validity of DS results; herein Chan et al. (10) argued that DS results can be generalized to the real world in the case of speed management. Godley et al. (11) concluded relative validity of DS in speed measurement, as participants revealed similar deceleration patterns in response to rumble strips in both instrumented car and simulator tests.

The purpose of this research is to analyze drivers’ speed fluctuations in the proximity of qualitative and quantitative DMS along two classes of highway. Dominant speeding patterns were inferred to identify individuals’ speed choice as they approached a DMS. The mean speeds were computed for four segments; prior to approaching DMS, in visible area, through reading the message, and after passing DMS. This study utilized a driving simulator to replicate drivers’ perception and behaviors while collecting speed data. This research attempts to determine if displaying messages on DMSs relate to drivers’ speeding behaviors.

**METHODOLOGY**

This study used a UC-win/Road driving simulator (DS), by FORUM8 (12) to collect data on drivers’ speed when approaching DMSs. The DS allows the researchers to create a driving environment and roadway geometrics identical to the real world conditions. A large network including ideal traffic settings, structures, landscaping, signage, and other related objects was built to duplicate the southwest region of the Baltimore Metropolitan area. Drivers’ attitudes and perceptions of speed variations were collected through a post-experiment survey. For the DS experiments, drivers were positioned to start on highway MD-100, 3.45 miles (5,550 m) west of I-95, traveling in the eastbound direction towards downtown Baltimore in off-peak traffic conditions. Two DMSs were mounted along the journey, the first (DMS1) placed on MD-100, 1.39 miles (2,240 m) from the start point and presented travel time information for two major alternative routes. The second (DMS2) was mounted on I-95, 1.56 miles (2,507 m) from the MD-100 entrance ramp and presented qualitative information of possible delay and lane closure. Table 1 presents the specifications of the two corridors in which the two DMS were mounted on them. Figure 1 displays driving simulator environment in the proximity of DMS1.

**TABLE 1** Specifications of Two Study Sites and Their Associated DMS

<table>
<thead>
<tr>
<th>Features</th>
<th>MD-100</th>
<th>I-95</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed analysis length</td>
<td>900 m</td>
<td>1,350 m</td>
</tr>
<tr>
<td>Highway speed limit (mph)</td>
<td>55 (88.5 km/hr)</td>
<td>65 (105 km/hr)</td>
</tr>
<tr>
<td>Number of highway lanes</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>DMS</td>
<td>DMS1</td>
<td>DMS2</td>
</tr>
<tr>
<td>Distance travelled from origin to reach DMS</td>
<td>2,240 m</td>
<td>8,050 m</td>
</tr>
<tr>
<td>DMS message type</td>
<td>quantitative</td>
<td>qualitative</td>
</tr>
</tbody>
</table>
The speed analysis in this study is based on four segments of the roadway surrounding each DMS. The analysis is performed for each DMS individually to test the significance of speed variation when drivers approach DMS and pass through it. The segments are listed as initial, visible, readable, and post-DMS display zones. To recapitulate on the New York State Thruway Authority guideline (4) for the sightline of a DMS and its compliance with the MUTCD (5) on the provided visible and readable areas, the distances selected for analysis of this research differ. This study could not fully adhere to the MUTCD recommendations considering the standards are based on the real world conditions. Distances for the four segments were qualitatively determined according to the research team’s driving experiments and are compliant with the driving simulator network. The four segments’ lengths and positions for DMS1 and DMS2 are exhibited in Figure 2 and Figure 3, respectively. As displayed, all distance ranges are successive, except there is a 310 m gap between S1 and S2 in DMS2. The reason was the presence of a horizontal curve along I-95 that could affect the free flow speed in the initial speed zone.

To better clarify the four defined zones, S1 or initial speed area represents the average speed of drivers not influenced by DMS (i.e., drivers did not observe DMS in their sight distance). S2, visible area, represents the average speed of drivers when they noticed that they were approaching a DMS, but could not read its content. S3 represents the average speed when drivers were close enough to read the sign. S4, post-DMS zone, addresses the average speed when drivers passed the DMS. The drivers’ instant speeds were recorded by the DS software for many snapshots per second. For each experiment, the mean speeds were calculated over the entire snapshots within each of the four segments’ length to prevent speed noise.
FIGURE 2 Description of the four segments for DMS1 speed analysis.

FIGURE 3 Description of the four segments for DMS2 speed analysis.

STUDY DATA

To solicit participants for this study, fliers were distributed across Baltimore County, Baltimore City, and Morgan State University (MSU) campus. By reimbursing the volunteers for their participation in the study, the study was able to gain an unbiased sample from various socioeconomic backgrounds. Overall, 102 people participated in the study wherein they totally completed 577 experiments. Sixty-four percent of the participants were males with the largest number of subjects falling between 18 and 25 years old. The skewed age distribution was due to the fact that many of the subjects were either MSU students or their associates. Participants had practice tests to get familiarized with the simulator’s features and the built network. Subjects drove in random traffic scenarios, 1 to 12 times, with an average of 5.7 times per subject and the average travel time of 22 minutes. Table 2 presents the descriptive statistics of the participants’ socio-economic characteristics (gender, age group, education level, income stratum, car ownership, and annual driving mileage) and network familiarity collected through the pre-experiment questionnaire. For more information on the experiment design, interested readers are referred to Jeihani and Ardeshiri (13).
**TABLE 2 Descriptive Statistics of Subjects’ Characteristics**

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>States</th>
<th>Percentages</th>
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</thead>
<tbody>
<tr>
<td>Gender</td>
<td>Female</td>
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</tr>
<tr>
<td></td>
<td>Male</td>
<td>64</td>
</tr>
<tr>
<td>Age</td>
<td>&lt; 18</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>18-25</td>
<td>36</td>
</tr>
<tr>
<td></td>
<td>26-35</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>36-45</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>46-55</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>&gt; 55</td>
<td>13</td>
</tr>
<tr>
<td>Education level</td>
<td>High school or less</td>
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<td></td>
<td>College degree</td>
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<tr>
<td></td>
<td>Post-graduate</td>
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<tr>
<td>Household income level</td>
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<td>23</td>
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<tr>
<td></td>
<td>$20K- $30K</td>
<td>18</td>
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<td>$30K- $50K</td>
<td>13</td>
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<tr>
<td></td>
<td>$50K- $75K</td>
<td>16</td>
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<tr>
<td></td>
<td>$75K- $100K</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>&gt; $100K</td>
<td>17</td>
</tr>
<tr>
<td>Annual mileage driven</td>
<td>≤ 8,000</td>
<td>29</td>
</tr>
<tr>
<td></td>
<td>8,001 - 15,000</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>15,001 - 30,000</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>≥ 30,000</td>
<td>11</td>
</tr>
<tr>
<td>Route familiarity</td>
<td>Unfamiliar</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>Somewhat familiar</td>
<td>43</td>
</tr>
<tr>
<td></td>
<td>Familiar</td>
<td>32</td>
</tr>
</tbody>
</table>

* holding learner’s permit

**ANALYSIS AND DISCUSSION**

**Site 1**

DMS1 displayed five different quantitative messages. The aggregate speed analysis results showed steady speed increase from initial speed area (S1) to visible (S2) and to readable (S3) zones, followed by a slight speed decrease in the post-DMS zone (S4). Figure 4 illustrates the average speed of all experiments (after data cleaning) for each of the four segments. Although the changes from S2 to S3 and S3 to S4 were trivial, the speed pattern which a majority of the cases replicated was unexpected to the researchers. Possible reasons for this less common pattern are conceivably based on limitations and lack of a control condition (inactive sign) for the first site, which consequently hindered purifying the impact of DMS on speed from the effect of roadway physical specifications. Figure 5 depicts five typical speed patterns along the four segments and represents the distribution of subjects’ speed choice in response to DMS. Among all, pattern-IV was more compatible with the study’s hypothesis. While the aggregate speed variation replicated pattern-III, it is possible that the majority of the individual cases (44 percent) were placed in pattern-III. According to the proportion of each pattern presented in Figure 5, after pattern-III, pattern-V, which indicates a zigzag speed trend (veering up and down), accounts for the second high frequency speed pattern. Pattern-IV (the expected pattern) accounts for the third highest percentage type.

In nearly 24 percent of the experiments, drivers’ mean speeds in S1 were higher than 60 mph (97 km/hr), when the posted speed limit was 55 mph (88.5 km/hr) in site 1. By focusing
only on speeders, the distribution of speed pattern leads to a more interpretable driving behavior. The last row of Figure 5 presents the proportion of each pattern controlled for speeds higher than 60 mph (97 km/hr). Compared to the previous general classification, fast drivers complied more with the adaptive patterns (i.e., II and IV) and less with the uncommon pattern-III. The significant difference between the average and fast drivers’ speed behavior, demonstrates the lowering effect of DMS on speed limit violators.

![Figure 4](image)

**FIGURE 4** Aggregate speed variation in the four segments of the DMS1.

![Figure 5](image)

**FIGURE 5** Five typical speed patterns and their proportions for DMS1.

### Site 2

DMS2 had both inactive and (qualitative) active message scenarios. In this site, the majority of drivers imitated speed pattern-V, starting with a speed increase from the initial speed area to the visible zone, followed by a speed decrease from the visible to readable area, and ultimately another speed increase passing the DMS line. Figure 6 compares the average speeds of the four segments for the two DMS conditions, active and inactive, on I-95 with 65 mph (105 km/hr) posted speed. As expected, the active DMS had a more intense speed fluctuation; however, statistical tests are required to reveal the significance of difference. Analysis of variance (ANOVA) was conducted to test whether the speed reductions were statistically different between DMS conditions (on and off) and the four segments along the site 2. Table 3 shows the F-test derived from a two-factor ANOVA and indicates that there is statistically significant difference between the average speeds in the four segments. However, DMS conditions neither alone, nor in the interaction form with the segment factor is statistically significant.

Furthermore the results of paired $t$-test at a 0.05 significance level indicated that the active DMS did not change drivers’ speed significantly compared to the inactive DMS. In other words, none of the four segments’ average speeds in the active DMS were statistically different from their corresponding points in the inactive condition at $\alpha = 0.05$ (e.g. 97.1 and 95.6 in the
visible segment and 92.8 and 94.8 in the readable segment). In addition, this study did not
evaluate the effects on DMS slowdowns due to unexpected messages relevant to public safety
(i.e. AMBER Alert) or unpredictable conditions. Displaying these additional messages may have
presented a more intense speed fluctuation. However, unlike the DMS1, a significant reduction
in average speed was observed when drivers entered the active DMS readable area from the
visible area (i.e. 97.1 and 92.8) followed by a significant increase in the average speed when they
passed the DMS line.

![Figure 6 Aggregate speed variation in the four segments of the DMS2.](image)

**TABLE 3 ANOVA Results for DMS2**

<table>
<thead>
<tr>
<th>Factor</th>
<th>d.f.</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>DMS condition</td>
<td>1</td>
<td>0.242</td>
<td>0.623</td>
</tr>
<tr>
<td>Segment</td>
<td>3</td>
<td>3.456</td>
<td>0.016</td>
</tr>
<tr>
<td>Interactive effect (DMS condition × Segment)</td>
<td>3</td>
<td>0.620</td>
<td>0.602</td>
</tr>
</tbody>
</table>

While studies based on survey questionnaires suggested a substantial slowdown in the
traffic stream in the DMS neighborhood (2), our DS finding is in line with the past studies which
performed speed analysis based on actual or simulator data (7, 9). The post-experiment survey in
this study demonstrated that the subjects had a quite precise perception of their speed variation in
the DMS neighborhood. According to the survey results, only 19 percent of the subjects declared
that they significantly slowed down their speed to read the message. While 54 percent believed
their speed reduction was insignificant, the remaining 27 percent indicated no change in their
speed in the proximity of DMS.

**CONCLUSIONS**

Speed data was collected in an empirical study using driving simulator technique. The study data
comprised 560 long experiments by 102 subject drivers. Two DMSs located in two classes of
highways were replicated in a DS built-network. Four segments were defined to better evaluate
the speed fluctuations prior to, in the proximity of, and passing the DMS. The study found no
significant reduction in the driving speed to read the quantitative DMS; however, the average
speed decreased by 2.6 mph (4.3 km/hr) in the qualitative DMS’s readability zone compared to
the visibility zone and the change was significant at 98 percent confidence level. Corridor’s
speed limit, density, and driver’s speed appeared to be the most effective factors in speed
fluctuations in the proximity of DMS. Speed reduction occurred more frequently among speeders
and in the corridor with higher speed limit which had higher density. Statistical tests revealed that DMS conditions (active and inactive) caused no difference in the mean speed. Due to the driving cognitive loads in DS tests, similar to the real world situation, DMS cannot be the only source of speed variations as many other unaccountable environmental factors may influence drivers’ speed choice.

It is noteworthy that failing to simulate the brake lights of the leading vehicles in downstream traffic confronting a DMS is a major restriction of DS studies. It is postulated that brake lights cause a psychological chain reaction and substantially affect traffic slowdown. Since the probe vehicle in the DS study is the only vehicle about to read the DMS, the subject’s driving behavior is somehow associated with other vehicles in the stream that are indifferent to the DMS. A real traffic stream compliant with microscopic flow characteristics surrounding the probe vehicle would be a future research direction to enhance the findings of typical DS studies.

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