SPEED REDUCTION PROFILES OF VEHICLES IN A HIGHWAY CONSTRUCTION ZONE

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A Report of the findings of:
Investigation of speed control methods in work zones

Project IHR-014
ILLINOIS COOPERATIVE HIGHWAY RESEARCH PROGRAM

Conducted by the
DEPARTMENT OF CIVIL ENGINEERING
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

For the
ILLINOIS DEPARTMENT OF TRANSPORTATION
In Cooperation with the
U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL HIGHWAY ADMINISTRATION

JUNE 1992
In response to roadway geometry and traffic control devices, motorists may change their speeds within in a work zone. Speed profile data were collected for 208 vehicles who traveled a 1.5-mile long section of a work zone, and speed reduction patterns were determined for Autos and Trucks. Four driver categories were identified based on the patterns. About 61% of the drivers reduced their speeds considerably after the first work zone speed limit signs, but nearly 15% of the drivers did not reduce their speeds until they neared the location of construction activities. About 11% of the drivers traveled at consistently high speeds and did not considerably reduce their speeds. The remaining drivers did not display a common pattern. The average speeds of Autos and Trucks were 5-18 mph and 1-12 mph, respectively, over the work zone speed limit. Vehicles decreased their speeds to the lowest level near the work space, but increased them after passing it. Even at the work space, about 65% of Autos and 47% of Trucks traveled faster than the speed limit. Autos and Trucks reduced their speeds by 3-13 mph and 3-12 mph, respectively, compared to their speeds at the beginning of the taper. The speeds at the beginning of the taper were used to group the vehicles into four speed groups. The maximum reduction in the average speed at different locations was greater with greater initial mean speeds; indicating that, on the average, the vehicles with higher initial speeds reduced their speeds more than the vehicles with lower initial speeds. However, the drivers in the higher initial speed groups kept higher speeds in the work zone than the drivers in the lower initial speed groups, even though the former group had greater speed reductions than the latter group.
ACKNOWLEDGMENT AND DISCLAIMER

This research report is based on the results of Project IHR-014-Investigation of Speed Control Methods in Work Zones. This study is sponsored by the Illinois Department of Transportation and the U. S. Department of Transportation, Federal Highway Administration. The authors would like to thank the Project Advisory Committee members for their comments and suggestions. The authors would also like to thank Michael H. Lee and Weixiong Zhao for their assistance in this study, and R. Pembroke and C. Wienrank for review of the report.

The contents of this report reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Illinois Department of Transportation or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.
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1. INTRODUCTION

Slowing down the speeding motorists in construction zones is a safety concern for highway officials. Most drivers slow down when they perceive a potential hazard on the road, such as the presence of crew or large equipment near the traveled lane (1). There are several questions that remain to be answered about work zone traffic control. Some of the questions are listed below. Where do drivers slow down in a work zone? Once drivers slow down, do they travel at the reduced speed throughout the work zone? How much speed reduction do the work zone speed limit signs induce? Where do drivers begin to increase their speeds within a work zone? Do faster drivers reduce their speeds more than the slower ones? In order to respond to these questions, speed profiles of vehicles in the work zone are needed.

From the speed profile data, velocity of a vehicle at different locations along the work zone can be obtained and the speed reduction effects of various traffic control devices and roadway features may be determined. The speed profile study provides information that is not available from the previous studies (2-7) which measured speed at one or two points within the work zones. The information from the speed profile study will help to understand drivers' behavior in work zones and to select more efficient and effective methods of traffic control.

This study was conducted to determine speeds of vehicles at different locations within a work zone in order to plot their speed profiles. The field experiment consisted of obtaining video images of vehicles as they traveled through the construction zone. The vehicles were video taped from the time they entered a 1.5-mile long study section until they left it. The speed profile data for 208 vehicles were collected, and a speed reduction pattern for each vehicle was generated.

This report discusses data collection, data reduction, speed characteristics, speed profile patterns, driver categories, speed reductions at different locations within a work zone, and effects of the initial speed on speed reduction. The terminology suggested by Lewis (8) is used, whenever possible, to identify different locations in a work zone. According to the terminology, a work zone is divided into four areas—advance warning, transition, activity, and termination area. The activity area is further divided into two spaces—buffer space and work space. It should be noted that the work space is only one small part of a work zone. The findings reported herein are based on the speed profiles of 151 vehicles whose speeds were not influenced by the presence of other vehicles in the work zone.
2. STUDY APPROACH

The study approach is based on finding speed profiles of vehicles in a construction zone and performing statistical analyses on the speed reduction effects of work zone roadway features and traffic control devices. The speed of a vehicle was monitored throughout the study section. Two video cameras were used to collect data as vehicles traveled in the work zone. A vehicle was labeled as "influenced" if it was slowed down by another vehicle in front of it, otherwise it was labeled as "uninfluenced." The "uninfluenced" vehicles were in free flow traffic traveling in their desired speed in the work zone. The findings of this study are based on the speed characteristics of the "uninfluenced" vehicles. The "uninfluenced" vehicles were further divided into two vehicle groups— the Autos group and the Trucks group. Autos included passenger cars, vans, and pick-up trucks. Those vehicles in the Truck group are of the tractor semi-trailer type.

Study Site

The construction zone was located on a rural section of Interstate 57 in Coles county near Mattoon, Illinois. The highway has two lanes per direction, but one lane in each direction was closed because of the construction. The work zone was about 3.5 miles long. The construction work was mainly repair of two bridge decks; one over State Route 16 and one about 2.5 miles to the south of Route 16. Other construction activities included patching, overlay, and shoulder reconstruction on the ramps of Route 16 and I-57. There is a full cloverleaf interchange at Route 16, but the inner loops from Route 16 (on ramps) to the highway were closed.

The speed limit inside the construction zone was 45 mph for all vehicles. However, outside the work zone it was 65 mph for cars and 55 mph for heavy trucks. The traffic control plan (TCP) used in the work zone was one of the standard TCPs of the Illinois Department of Transportation (IDOT) which is prepared in accordance with the guidelines given in the Manual on Uniform Traffic Control Devices (MUTCD) (9). Figure 2.1 schematically shows the signs used for traffic control in this work zone.

The profile of the highway in the study section and the locations of vertical curves as well as the Influence Points are shown in Figure 2.2. There were two sag curves and two crest vertical curves in the study section. One crest vertical curve, located in the middle of the study section, was approximately 2,800 feet long. It started 400 feet before the DeWitt Road overpass and ended 200 feet before Rt 16. Between the first sag curve and this crest curve, there is a very short section with a 3% upgrade slope. The speed reduction due to the uphill section, if any, would be noticeable on the trucks but not on the cars (10). The other three curves had very gentle slopes and would not significantly affect the speed of vehicles.
Figure 2.1 Work zone signs on SB I-57 during speed profile study
Data Collection

The field experiment consisted of obtaining the speed of the vehicles at various locations as they traveled through the construction zone. The speeds were obtained using video images of the vehicles. Video images of vehicles have been previously used for data collection (11), however, the data collection approach of this study is unique. A vehicle was video taped from the time it entered the study section until it exited from the section. The study section was about 1.5 miles in length and was within the traffic control zone of this site. The study section was divided into two segments by the field of view of two cameras. The first segment was 4,800 feet long and was video taped from Camera Location 1. The following segment. Segment 2, was 5,600 feet long and was video taped from Camera Location 2. There was a 1,600 feet long overlapping segment that was video taped from both camera locations. The data collection setup is shown in Figure 2.3.

Each segment was further divided into smaller intervals by roadway markers. Two markers defined an interval. The markers were established along the highway to serve as reference points for computing the distance and time a vehicle spent in the interval. The markers were either permanent or temporary. The permanent markers were located on the roadside or in the median of the highway (e.g. bridge abutment, signs, or light posts). The temporary markers were plastic posts placed on the roadside when a permanent marker was not available at that location. The markers were spaced 400 feet to 700 feet from each other. A total of 30 markers were established. However, normally only 21 markers were used for each vehicle. The remaining 9 markers were considered supplementary, and were used only when the time reading for a nearby marker was missing.

Data was collected from May 30 to June 1 of 1990, during weekdays under normal weather conditions. To eliminate the effects of platooning, only vehicles which were in free flow traffic at the beginning of the study section were video taped. A total of 208 vehicles were video taped during the three days of data collection. The Average Daily Traffic (ADT) on this section of the freeway was around 12,000 vehicles, with approximately 22% heavy commercial vehicles (12).

Data Collection Teams

There were two data collection teams. The First Team was located at Camera Location 1 and the Second Team at Camera Location 2. Each team consisted of two members, a camcorder equipped with a powerful zoom lens and an accurate clock, a citizens band radio (CB), a tripod, and a note pad. The communication between the two teams was handled by the CBs. On each team, one person video taped the vehicle and the other one talked on the CB to a person at Camera Location 2, so that the same vehicle was video taped by both teams. The tripods were used to obtain steadier pictures, while
Figure 2.3 Data collection setup for speed profile study

Camera Location 1

Camera Location 2

2565 ft

3264 ft

2620 ft

2586 ft

I-57 SB

I-57 NB

Rt. 16

Dewitt

Segment 1

Segment 2

Study Section

NOT TO SCALE

1638 ft
the note pads were used to record information about the vehicles. The First Team identified a free flowing vehicle that was about to enter the study section and started video taping it. A brief description of the vehicle was given to the Second Team. As the vehicle approached Segment 2, more information about the vehicle and its location was given to the Second team so the same vehicle was video taped by both teams. In overlapping intervals, both teams video taped the same vehicle. The overlapping intervals were used to check the speeds computed from two video images and to confirm that the same vehicle was video taped by both teams. Each vehicle's description and the time of day it traveled in the study section was written in the field notes for later use in data reduction.

Camera Locations

Camera Location 1 was on DeWitt Road which is about 2,600 ft north of Route 16. DeWitt Road is an east-west, two-lane, two-way road (with 50 mph speed limit) which goes under I-57. From Camera Location 1, Team 1 could see the vehicles before they entered the lane closure taper until they traveled a distance of 4,800 ft, which is the end of the overlapping intervals as well as the end of Segment 1.

Camera Location 2 was on Route 16, which is a four lane road separated by a grass median. From Camera Location 2, Team 2 could see a vehicle when it was on the Dewitt Road overpass, which was the beginning of the overlapping intervals as well as Segment 2. From Camera Location 2, one could video tape the vehicle until it traveled a distance of 5,600 ft which was the end of Segment 2 and the study section.

Data Reduction

The data reduction was very labor-intensive; thus, an extensive amount of time was spent to get meaningful data from the video records of the vehicles. Descriptions of each vehicle were carefully examined once again to confirm that the same vehicle was video taped by the two teams. It was also checked to see whether this vehicle exited from the ramps or reached a slow-moving vehicle. This was discerned by watching the video tapes of the vehicle. If it seemed that the taped vehicle was slowed down by another vehicle, the taped vehicle was tagged as suspected for platooning (influenced).

Out of 208 vehicles, 57 vehicles were tagged as influenced vehicles. The remaining 151 vehicles were labeled as uninfluenced. The uninfluenced vehicles were divided into three vehicle types: passenger cars, tractor semi-trailer trucks, and vans and others (such as jeeps and pick-up trucks). There were 74 cars, 49 trucks, and 28 vans and other vehicles in the uninfluenced group.

The speed characteristics of the cars group were compared to
those of the vans group to determine whether there were significant differences for the two vehicle types. The results of the comparison indicated that the cars and vans had very similar speed characteristics. Thus, the cars and vans were combined into one group which is called Autos.

Therefore, the findings in this report are for two vehicle groups - the Autos group, which has 102 vehicles, and the Trucks group, which has 49 vehicles. Further details on data reduction are given in Appendix A. During data collection for this group, there were no police present in the work zone.

**Speed at Influence Points**

Throughout the construction zone, there are traffic control signs and roadway features that may influence speed of a vehicle. An Influence Point (IP) is defined as a location within the construction zone that may have such a sign or roadway feature. Thirteen IPs, labeled "a" through "m", were identified in this study. The Influence Points and their distances from the beginning of the study section are listed in Table 2.1. The speed of a vehicle at these Influence Points was determined using the speed profiles.

Table 2.1 Influence Points and their distances from the beginning of the study section

<table>
<thead>
<tr>
<th>INFLUENCE POINTS</th>
<th>LOCATION IN WORK ZONE</th>
<th>DISTANCE (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>Beginning of the taper</td>
<td>600</td>
</tr>
<tr>
<td>b</td>
<td>End of the taper</td>
<td>1600</td>
</tr>
<tr>
<td>c</td>
<td>Before 1st speed limit signs</td>
<td>2100</td>
</tr>
<tr>
<td>d</td>
<td>At 1st speed limit signs</td>
<td>2600</td>
</tr>
<tr>
<td>e</td>
<td>After 1st speed limit signs</td>
<td>3100</td>
</tr>
<tr>
<td>f</td>
<td>Near the end of upgrade section</td>
<td>4300</td>
</tr>
<tr>
<td>g</td>
<td>1200 feet before Rt. 16 bridge</td>
<td>4800</td>
</tr>
<tr>
<td>h</td>
<td>600 feet before Rt. 16 bridge</td>
<td>5400</td>
</tr>
<tr>
<td>i</td>
<td>At Rt. 16 bridge</td>
<td>6000</td>
</tr>
<tr>
<td>j</td>
<td>500 feet after Rt. 16 bridge</td>
<td>6500</td>
</tr>
<tr>
<td>k</td>
<td>1000 feet after Rt. 16 bridge</td>
<td>7000</td>
</tr>
<tr>
<td>l</td>
<td>Before 2nd speed limit signs</td>
<td>7900</td>
</tr>
<tr>
<td>m</td>
<td>Second speed limit signs and end of the study section</td>
<td>8300</td>
</tr>
</tbody>
</table>
Measurement Errors

The speed profile of each vehicle was reviewed to check whether there were any noticeable errors (e.g. a sudden increase or decrease in speed). Common sources of noticeable errors could be: Mistakes in computing time or distance, input errors, or errors due to missing data. Possible sources of noticeable errors were identified and corrected.

Moreover, computational errors and sensitivity of the computed speed to the input values were examined. The computational errors, unlike the noticeable errors, are not due to some mistakes in the process, but due to the procedures used to compute the speed. For instance, there will be errors in reading the time a vehicle passes a marker (e.g. 1/30 of a second). This error in turn will affect the computed speed.

Several sources of computational errors were identified and their effects on speed were calculated. The sources are: Errors in measuring the longitudinal distances between the markers, the lateral distances from the markers to the highway, and the distance between the camera and the road; errors due to the vehicle’s location in the lane, and the width of vehicle (i.e. car vs truck). The procedures for calculating the magnitude of the computational errors are given in Appendix B. In general, the computed speed could be in error by 1 mph or less due to these errors.

Effects of Upgrade Slope on Speed

From field observation of the speeds, it seemed that any speed reduction due to the upgrade took place before reaching the overpass on DeWitt Road. Examination of the speed profiles indicated that the upgrade section did not significantly reduce the speed of cars, but may have reduced the speed of trucks.

After the construction work was completed, adjustment data were collected to determine the speed reduction effects of the upgrade section. The mean speed reduction was 1 mph for cars and 4.96 mph for trucks. The speed change for most of the cars was concentrated between -1 and 2 mph, and for most of the trucks the concentration was between -3 and -6 mph. Appendix C provides further information on the data collection and data analysis. It was not possible to separate the speed reduction effects of the speed limit signs from that of the upgrade.
3. SPEED CHARACTERISTICS AND DRIVER CATEGORIES

Summary of Speed Characteristics

At each Influence Point (IP), the maximum, minimum, average speed, and standard deviation of speed of Autos and Trucks were computed. These statistics are summarized in Table 3.1. A detailed discussion of speed characteristics is given in Appendix D. Autos and Trucks showed very similar speed characteristics in the study section. The mean speeds of Trucks were about 4-7 mph lower than that of Autos at all Influence Points. The mean speed profile for Trucks parallels that of Autos, as shown in Figure 3.1.

The construction zone over the bridge (work space) was delineated by Jersey Barriers. There were Jersey Barriers over a length of about 250 ft. However, the open lane was sufficiently wide (around 15 ft) not to give the feeling of going through a narrow lane. Although a previous study indicates that the concrete safety shape (Jersey) barriers do not have impact on highway capacity even when they are closer than 6 ft to the traveled lane (13, p. 3-11), vehicles in this study decreased their speed when they went through the work space (see Table 3.1). The main reason for the speed reduction seems to be due to the construction activities in the work space and the presence of the concrete shape barriers at this location.

![Figure 3.1](image-url)

**Figure 3.1**

Average speed of vehicles at Influence Points in work zone.

- Speed (mph)
- Influence Points and distance (1000 ft)
- Autos
- Trucks
Table 3.1 Speed Characteristics Statistics for Autos and Trucks

<table>
<thead>
<tr>
<th>Influence Point</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Mean</th>
<th>Std. Dev</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Auto</td>
<td>Truck</td>
<td>Auto</td>
<td>Truck</td>
</tr>
<tr>
<td>a</td>
<td>46.1</td>
<td>45.5</td>
<td>79.0</td>
<td>68.8</td>
</tr>
<tr>
<td>b</td>
<td>43.7</td>
<td>38.3</td>
<td>77.9</td>
<td>66.4</td>
</tr>
<tr>
<td>c</td>
<td>44.8</td>
<td>38.9</td>
<td>78.7</td>
<td>66.3</td>
</tr>
<tr>
<td>d</td>
<td>41.7</td>
<td>40.2</td>
<td>77.7</td>
<td>67.0</td>
</tr>
<tr>
<td>e</td>
<td>39.3</td>
<td>39.8</td>
<td>75.2</td>
<td>65.4</td>
</tr>
<tr>
<td>f</td>
<td>42.8</td>
<td>38.0</td>
<td>73.1</td>
<td>61.7</td>
</tr>
<tr>
<td>g</td>
<td>43.0</td>
<td>36.2</td>
<td>73.2</td>
<td>61.2</td>
</tr>
<tr>
<td>h</td>
<td>34.4</td>
<td>33.3</td>
<td>67.3</td>
<td>60.6</td>
</tr>
<tr>
<td>i</td>
<td>24.8</td>
<td>35.3</td>
<td>67.2</td>
<td>59.7</td>
</tr>
<tr>
<td>j</td>
<td>29.8</td>
<td>36.8</td>
<td>68.1</td>
<td>62.5</td>
</tr>
<tr>
<td>k</td>
<td>41.2</td>
<td>42.1</td>
<td>68.7</td>
<td>62.4</td>
</tr>
<tr>
<td>l</td>
<td>44.7</td>
<td>41.9</td>
<td>69.3</td>
<td>62.1</td>
</tr>
<tr>
<td>m</td>
<td>41.8</td>
<td>40.5</td>
<td>72.8</td>
<td>64.8</td>
</tr>
</tbody>
</table>

Sta. Dev = Standard Deviation
Summary For Autos

The mean speed for Autos reduced from 63 mph at the beginning of taper (IP a) to 57 mph at 1,200 ft before the bridge (IP g), and continued decreasing to 50 mph at the bridge (IP i). Then, it increased to 56 mph at 1000 ft after the bridge (IP k), and kept increasing until the vehicles reached the end of study section (IP m), see Table 3.1.

Autos traveled at a wide range of speeds at all Influence Points as indicated by the large standard deviations. The speeds of Autos over the bridge were as low as 24 and as high as 67 mph. At 500 feet after the bridge, the speed range for Autos was from 29 mph to 68 mph. The average speeds and speed variances at the first and the second pair of speed limit signs were almost equal. At both locations, the average speeds of Autos were 12 to 13 mph higher than the 45 mph speed limit.

Percentage of Autos Exceeding a Speed Level

The percentage of vehicles exceeding a given speed decreased over the bridge, but increased to the same levels as before when drivers passed the bridge. The percentage of Autos exceeding 65 mph was 38% at the beginning of the taper, 16% at the first speed limit signs, 5% at 500 ft after the first speed limit signs, 10% at 1200 ft before the bridge, 4% at the bridge, 6% at 1000 ft after the bridge and 11% at the second speed limit signs. Similar trends were observed at other speed levels, as shown in Figure 3.2.

It is important to note that the percentage of Autos exceeding a given speed at the second construction zone speed limit signs (IP m) almost reached the level of the first speed limit signs (IP d). This indicates that, on the average, the drivers decreased their speeds to the lowest level near the work space, but after passing it they accelerated to the same speeds they had at the first speed limit signs.

The percentage of Autos exceeding the speed limit over the bridge (IP i) was the lowest compared to other locations; however, nearly 65% of Autos traveled faster than 45 mph at this location. The curves in Figure 3.2 roughly parallel each other and appear to be in a "W" shape. The shape indicates that the drivers increased their speeds after passing the first speed limit signs (IP d) and before arriving at the bridge (IP i). There was 3,400 ft of distance between IP d and IP i. The drivers may have perceived this distance to be too long, so they increased their speed.

Summary For Trucks

From Table 3.1, it can be found that the average speed for Trucks reduced from 57 mph at the beginning of the taper (IP a) to 46 mph at the bridge (IP i), and then increased to 52 mph at the end of the study section (IP m).
The range of speed for Trucks was narrower than the range for Autos, as reflected by the smaller standard deviations for Trucks (it varied between 4.75 and 5.86). Interestingly, the largest variation in speed did not occur over the bridge, but was at the end of the taper and before the first speed limit signs. Over the bridge, the speed of Trucks was as low as 35 mph and as high as 60 mph.

**Percentage of Trucks Exceeding a Speed Level**

The percentages of Trucks exceeding a given speed at different locations within the study section are shown in Figure 3.3. The percentage of Trucks exceeding 65 mph was 4% at the beginning of the taper and 2% at the first speed limit signs. No trucks were exceeding 65 mph at the bridge or at the second set of speed limit signs. The percentage of the Trucks exceeding a given speed decreased over the bridge and increased, in general, to the same levels as before the bridge.

It is important to note that Truck drivers, similar to Auto drivers, decreased their speeds to the lowest level near the construction activities, but after passing them, they accelerated to the same speeds they had before. The percentage of Trucks exceeding a given speed at the first and second set of construction zone speed limit signs (IP d and IP m) is almost equal. The percent exceeding curves appear to be parallel and have a "W"
figure 3.3
percent of trucks exceeding given speeds
at influence points in work zone

% exceeding

45 mph
47 mph
50 mph
55 mph

60 mph
65 mph

influence points and distance (1000 ft)

shape. there were more drivers exceeding a given speed at the
first set of speed limit signs than at the bridge.

speed profile patterns

a review of speed profiles for 151 vehicles (102 autos and 49
trucks) indicated that there are certain speed reduction patterns
that are repeated by many drivers. first, the common speed
profiles for autos and trucks were identified separately. then, it
was observed that some autos and trucks have similar speed
profiles. based on their speed profile patterns, the drivers were
grouped into four general categories. the number of autos and
trucks and the total number of vehicles in each category are given
in table 3.2 and figure 3.4. the general description of a category
would apply to autos as well as to trucks.

the criteria for the classification were the visual
examination of the speed change patterns and a quasi quantitative
measure of the speed change. vehicles that showed similar speed
profiles were grouped into one category. if the speed change over
a significant portion of the study section was less than 5 mph for
autos and less than 4 mph for trucks, it was attributed to expected
speed fluctuation and was not used as a criteria in the
classification. the descriptions of these categories are given
below.
### Table 3.2. Number of autos and trucks in each driver category

<table>
<thead>
<tr>
<th>Category</th>
<th>Autos</th>
<th></th>
<th>Trucks</th>
<th></th>
<th>Total</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td># of veh.</td>
<td>percent</td>
<td># of veh.</td>
<td>percent</td>
<td># of veh.</td>
<td>percent</td>
</tr>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.1</td>
<td>25</td>
<td>24</td>
<td>12</td>
<td>25</td>
<td>37</td>
<td>24</td>
</tr>
<tr>
<td>1.2</td>
<td>24</td>
<td>23</td>
<td>10</td>
<td>20</td>
<td>34</td>
<td>22</td>
</tr>
<tr>
<td>1.3</td>
<td>11</td>
<td>11</td>
<td>11</td>
<td>23</td>
<td>22</td>
<td>15</td>
</tr>
<tr>
<td>sub total</td>
<td>60</td>
<td>58</td>
<td>33</td>
<td>68</td>
<td>93</td>
<td>61</td>
</tr>
<tr>
<td>2</td>
<td>17</td>
<td>17</td>
<td>4</td>
<td>8</td>
<td>21</td>
<td>14</td>
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<td>11</td>
<td>11</td>
<td>5</td>
<td>10</td>
<td>16</td>
<td>11</td>
</tr>
<tr>
<td>4</td>
<td>14</td>
<td>14</td>
<td>7</td>
<td>14</td>
<td>21</td>
<td>14</td>
</tr>
</tbody>
</table>

### Figure 3.4
Distribution of drivers in different categories

![Bar chart showing the distribution of drivers in different categories](chart.png)
Driver Category 1

Category 1 represents the drivers who reduced their speeds around the first set of speed limit signs. Some drivers in this category had further speed reduction at the work space (over the Rt 16 bridge). The drivers in Category 1 are further divided into three sub-categories (groups).

Driver Category 1.1 The first group in Category 1 represents the drivers who decreased their speeds around the first work zone speed limit signs and had further speed reductions at the bridge. Usually, the latter speed reduction was greater than the former one. The speed profile for this group was similar to that of car #197 or truck #54. Figure 3.5 shows the speed profiles for these vehicles. Approximately 24% of Auto drivers and 25% of Truck drivers belong to this group. Generally, the speeds of the Autos before the bridge, unlike the speeds of the Trucks before the bridge, were much higher than 45 mph.

![Figure 3.5](image)

Typical speed profile for drivers in Category 1.1

Driver Category 1.2 The second group in Category 1 represents the drivers who slowed down (sharply) at both the first speed limit signs and the bridge, but between these two points increased their speeds. Their speed profiles resembled to a "W" shape. The speed profiles for car number #153 and truck #151, as shown in Figure 3.6, represent typical speed profiles for this group. About 23%
of Auto drivers and 20% of Truck drivers were placed in this group.

![Figure 3.6](image)

**Figure 3.6**

Typical speed profile for drivers in
Category 1.2

**Driver Category 1.2**

The third group in Category 1 represents the drivers who reduced their speed around the first speed limit signs and kept traveling at the reduced speed until they passed the bridge. After passing the bridge some drivers in this group increased their speeds. The speed profile for this group was similar to that of car #67 or truck #60, as shown in Figure 3.7. About 11% of Auto drivers and 23% of Truck drivers belong to this group.

**Driver Category 2**

The criteria for Category 2 was that the drivers traveled faster than the speed limit and had a speed reduction less than 5 mph for Autos and 4 mph for Trucks before IP e. That means they basically ignored the first speed limit signs, but began to slow down when they arrived at the bridge. The speed profiles for car #108 or truck #166 (see Figure 3.8) represent the drivers in Category 2. Nearly 17% of Auto drivers and 8% of Truck drivers were placed in this category.
Driver Category 3

Category 3 includes those drivers that ignored both the first speed limit signs and the construction activities over the bridge. Examples of the drivers in this category are the driver of car #43 and truck #192; (see Figure 3.9). They drove through the work zone at almost a constant speed which was higher than the 45 mph speed limit. The Auto drivers in this category maintained a speed of approximately 60 mph or higher, and Truck drivers traveled at a speed between 50 and 60 mph. The speed fluctuation for this group was very small (5 mph or less). About 11% of Auto drivers and 10% of Truck drivers were grouped into this category.

Driver Category 4

The fourth category is called "others", which includes those vehicles that could not be classified into categories 1-3. Some of the drivers in Category 4 reduced their speed at the first speed limit signs, but did not slow down at the bridge. Some of them even increased their speeds while passing the work space. Figure 3.10 shows the speed profiles for car #26 and truck #34 which were placed in this category. About 14% of Auto drivers and 14% of Truck drivers belong to Category 4.
Importance of Categorizing Drivers

Knowing the nature and extent of the speeding problems in a work zone would help to select appropriate counter measures which may result in more effective traffic control plans. Drivers in the work zone showed distinct speed reduction behavior. Measures taken to slow down the drivers in Category 3 who ignored the speed limit signs may be different from the measures for the drivers in Category 1, who reduced their speed, but not to the desired level.

The locations at which the drivers slowed down or speeded up are the critical points in a construction zone. Knowing these points would help to place the signs at the appropriate locations. For instance, the traffic control signs to encourage the drivers to reduce their speed should be at the beginning of the work zone; while the signs to encourage the drivers to maintain the reduced speed should be before or at the points where the drivers begin to increase their speeds.

The distribution of drivers in the four categories indicates that 61% of drivers reduced their speed considerably after the first construction zone speed limit signs (refer to Figure 3.4). Category 1.3 is the ideal pattern. Drivers in this category reduced their speed around the first speed limit signs and kept the reduced speed until they passed the construction activities. And drivers should be encouraged to follow this pattern. Placing additional
speed limit signs between the first speed limit signs and the work space may persuade the drivers in Category 1.1 to slow down further, and may discourage the drivers in Category 1.2 from increasing their speed before the work space. The suggested traffic control methods should be experimented before implementation can be justified.

Furthermore, the speed reduction patterns of drivers may be used to determine the location of work zone signs that would result in more desirable speed reduction patterns. The drivers in Category 1.2 may have increased their speeds because they perceived that the work space was too far from the first speed limit signs. The location of the signs and the length of section before the work space should be such that most drivers are encouraged to follow the speed limit. Since 61% of drivers reduced their speeds around the first speed limit signs and 75% of all drivers (in both Category 1 and 2) reduced their speeds near the work space, more speed reduction may be achieved if the work space is closer to the beginning of the work zone.

Traffic control plans should be carefully prepared in order to obtain a higher level of compliance from the drivers. Drivers complain about marking a long stretch of highway as the construction zone without any construction activities (14). Such a practice would reduce the credibility of the work zone signs. The speed profiles for the drivers in Category 2 indicate that this group delayed speed reduction until they actually saw the
construction activities. The length of construction zones should be limited, whenever possible, to the section that is actively under construction.
4. SPEED REDUCTIONS AT INFLUENCE POINTS

The speeds at all IPs were compared to the speeds at the first IP (IP a). Additionally, speeds at selected pairs of IPs were compared with each other. The speed difference at a given Influence Point compared to a reference Influence Point was computed for each vehicle. Paired t-tests were used to compare the speed differences between pairs of Influence Points.

In a paired t-test, for a given pair of IPs, the mean of speed differences rather than the difference of the mean speeds is used to make statistical inferences. The results from the paired t-test analysis would help to examine how roadway features and traffic control devices affected the speed of vehicles and whether or not the effects were statistically significant.

For Autos

Reductions Compared to the Speed at the Beginning

A summary of speed changes between all IPs and IP a (beginning of the taper) is shown in Table 4.1. The average speed reductions varied from 2.5 mph to 13.4 mph. As drivers traveled further into the work zone the reduction first increased, then slightly decreased, and finally reached its maximum value at the bridge. After passing the bridge, the speed reductions continuously decreased until vehicles exited the study section (also refer to Figure 4.1).

The standard deviations listed in Table 4.1 reflect the degree of the concentration of the speed reductions. For example, at Influence Point b, the standard deviation was 2.80 mph, which is smaller than the standard deviation of 9.02 mph at IP i. This means the speed reductions at IP b were more concentrated than that at IP i.

The observed range for 90% of the speed changes at each Influence Point is also shown in Figure 4.1. Since the speed reductions were not normally distributed, the standard deviations should not be used to find the confidence level. For example, at IP f, the standard deviation was 6.08 mph and the mean speed reduction was 6.7 mph. For a standard normal distribution, it is expected to have 90% of the observations within the range of 1.645 times the standard deviation. If the speed reduction had been normally distributed, then 90% of speed reductions would have been within 16.7 to -3.3 mph. However, 90% of the observed speed reductions were within 18.4 to -0.7 mph.

The speed reduction frequency distributions for Autos and Trucks are given in Figures 4.2 through 4.13. It should be noted that almost all of the frequency plots show a small percentage of drivers who reduced their speeds by a large amount. These drivers are represented by the left tail of the frequency curves.
Table 4.1. Average of individual vehicle speed changes between pairs of influence points for Autos

<table>
<thead>
<tr>
<th>Influence Points Compared</th>
<th>Average Speed Differences</th>
<th>Standard Deviation</th>
<th>Standard Error</th>
<th>Confidence Level Speeds Are Different</th>
<th>Observed Range for 90% of Speed Changes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Lower Limit</td>
</tr>
<tr>
<td>(IP b)-(IP a)</td>
<td>-2.5</td>
<td>2.80</td>
<td>0.28</td>
<td>99.99</td>
<td>-8.5</td>
</tr>
<tr>
<td>(IP c)-(IP a)</td>
<td>-3.4</td>
<td>3.76</td>
<td>0.37</td>
<td>99.99</td>
<td>-10.3</td>
</tr>
<tr>
<td>(IP d)-(IP a)</td>
<td>-5.2</td>
<td>4.67</td>
<td>0.46</td>
<td>99.99</td>
<td>-15.4</td>
</tr>
<tr>
<td>(IP e)-(IP a)</td>
<td>-6.9</td>
<td>5.21</td>
<td>0.52</td>
<td>99.99</td>
<td>-15.8</td>
</tr>
<tr>
<td>(IP f)-(IP a)</td>
<td>-6.7</td>
<td>6.08</td>
<td>0.60</td>
<td>99.99</td>
<td>-18.4</td>
</tr>
<tr>
<td>(IP g)-(IP a)</td>
<td>-6.0</td>
<td>6.42</td>
<td>0.64</td>
<td>99.99</td>
<td>-18.4</td>
</tr>
<tr>
<td>(IP h)-(IP a)</td>
<td>-10.5</td>
<td>7.32</td>
<td>0.72</td>
<td>99.99</td>
<td>-23.8</td>
</tr>
<tr>
<td>(IP i)-(IP a)</td>
<td>-13.4</td>
<td>9.02</td>
<td>0.89</td>
<td>99.99</td>
<td>-29.1</td>
</tr>
<tr>
<td>(IP j)-(IP a)</td>
<td>-10.6</td>
<td>7.82</td>
<td>0.77</td>
<td>99.99</td>
<td>-25.1</td>
</tr>
<tr>
<td>(IP k)-(IP a)</td>
<td>-6.8</td>
<td>6.02</td>
<td>0.60</td>
<td>99.99</td>
<td>-17.2</td>
</tr>
<tr>
<td>(IP l)-(IP a)</td>
<td>-6.0</td>
<td>5.49</td>
<td>0.54</td>
<td>99.99</td>
<td>-15.8</td>
</tr>
<tr>
<td>(IP m)-(IP a)</td>
<td>-5.6</td>
<td>6.14</td>
<td>0.61</td>
<td>99.99</td>
<td>-16.3</td>
</tr>
</tbody>
</table>

| (IP h)-(IP j)             | 0.04                      | 4.47              | 0.44           | 6.76                                   | -5.7        | 7.9         |
| (IP c)-(IP e)             | 3.5                       | 3.56              | 0.35           | 99.99                                  | -1.0        | 10.8        |
| (IP d)-(IP m)             | 0.4                       | 5.42              | 0.54           | 50.21                                  | -7.8        | 10.2        |
| (IP g)-(IP k)             | 0.9                       | 4.37              | 0.43           | 94.83                                  | -5.5        | 9.8         |
Figure 4.1
Average speed change and observed range for 90% of changes for Autos

It is important to note that the frequency distributions are not bell-shaped. These shapes must be considered in making statistical inferences. The average speed reduction at the end of the taper, for example, was 2.5 mph which is the smallest reduction. This indicates that Auto drivers reduced their speeds, on the average, by 2.5 mph, when they reached the end of the taper; and, the range of reduction for 90% of the Autos was -0.7 mph to 8.5 mph. However, the speed reduction frequency distribution for the IP b shows that 33% of Autos reduced their speeds by less than 1 mph, and 53% reduced by less than 2 mph between the beginning and end of the taper. Thus, the average speed reduction is greatly influenced by the 47% of Autos who had larger than 2 mph reductions. Similar arguments can be made for IP c and IP d.

Auto drivers continued reducing their speeds after passing the taper. At the first speed limit signs (IP d), the mean speed reduction was about 5 mph, and the reduction fluctuated between 6 and 7 mph until the vehicles reached IP h. At IP h, which is about 600 ft before the bridge, the reduction increased to 10.5 mph. The largest average speed reduction was 13.4 mph which occurred over the bridge (IP i). The maximum speed reduction for Autos was 41.9 mph which also happened at the bridge. The standard deviation of speed differences increased as Autos approached the work space, and the largest one (9.02 mph) occurred at IP i.

After passing the bridge, the speed reductions became smaller as drivers traveled further away from the bridge. It is interesting to note that the reductions on either side of the

24
Figure 4.2
Distribution of speed changes at Influence Point b compared to a

Figure 4.3
Distribution of speed changes at Influence Point c compared to a
Figure 4.4
Distribution of speed changes at Influence Point d compared to a

Figure 4.5
Distribution of speed changes at Influence Point e compared to a
**Figure 4.6**
Distribution of speed changes at Influence Point f compared to a

![Histogram of speed changes with autos and trucks indicated]

**Figure 4.7**
Distribution of speed changes at Influence Point g compared to a

![Histogram of speed changes with autos and trucks indicated]
Figure 4.8
Distribution of speed changes at Influence Point h compared to a

Figure 4.9
Distribution of speed changes at Influence Point i compared to a
Figure 4.10
Distribution of speed changes at Influence Point j compared to a

Percent

-38 -34 -30 -26 -22 -18 -14 -10 -6 -2 2

Speed change (mph)

 Autos  Trucks

Figure 4.11
Distribution of speed changes at Influence Point k compared to a

Percent

-26 -22 -18 -14 -10 -6 -2 2 6

Speed change (mph)

 Autos  Trucks
Figure 4.12
Distribution of speed changes at Influence Point I compared to a

Figure 4.13
Distribution of speed changes at Influence Point m compared to a
bridge are very similar, indicating that the drivers after passing the bridge almost reached the speeds they had before the bridge.

Reductions Compared to Other Points

Further comparisons were made between pairs of IPs to compare the reductions at selected points. The first pair to be considered were the points 600 ft before and 500 ft after the bridge (IP h vs IP j). For this pair, the speed difference for Autos was 0.04 mph indicating that the speeds at 600 ft before and 500 ft after the bridge were not significantly different. This means that the drivers reduced their speed over the bridge, but increased it to the same level as before the work space.

The second pair of IPs compared were the points 500 ft before and 500 ft after the first speed limit signs (IP c vs IP e). The mean speed reduction was 3.5 mph which is a significant reduction. This means that on the average the speed was reduced 3.5 mph around the first speed limit signs. Assuming that at 500 ft before the first speed limit signs the drivers had reached their desired speed, the mean speed difference of 3.5 mph is mainly caused by the speed limit signs.

Thus, it is concluded that the speed limit signs were effective in reducing the average speed of Autos by 3.5 mph at a point immediately after the signs. It should be noted that the adjustment data (see Appendix C.) showed that the mean speed reduction for Autos caused by the upgrade segment would be less than 1 mph for the 1000 feet of travel.

The third pair of comparisons was between IP d and IP m, where the first speed limit signs and the second speed limit signs were located. The difference in reductions between these two Influence Points was 0.4 mph, which was not significant.

The last comparison pair was IP g and IP k (1,200 ft before and 1,000 ft after the bridge). The reduction difference between them was 0.9 mph. This indicates that after traveling about 1,000 ft past the bridge vehicles attempted to reach the speed they had 1,200 ft before the bridge.

For Trucks

Reductions Compared to the Speed at the Beginning

A summary of the speed changes between all IPs and the IP a (beginning of the taper) is shown in Table 4.2. The average speed reductions for Trucks varied from 2.6 mph to 11.5 mph. As drivers traveled further into the work zone the reduction first increased, then slightly decreased, and finally reached its maximum value at the bridge (see Figure 4.14) After passing the bridge, the speed reductions continuously decreased until vehicles exited the study section. The speed reduction distributions for Trucks are given in
Figures 4.2 through 4.13.

It should be noted that almost all of the speed reduction frequency distributions show a small percentage of drivers who had large speed reductions. These drivers are represented by the left tail of the frequency curves. It is important to note that the frequency distributions are not bell-shaped. Also it should be noted that the observed speed reduction ranges for trucks were narrower than those for autos (see Tables 4.1 and 4.2). These shapes clearly show that statistics based on the properties of the normal distribution cannot be used here.

![Figure 4.14](image)

Average speed change and observed range for 90% of changes for Trucks

The average speed reduction at the end of the taper, for example, was 2.7 mph, which is the second smallest reduction. This indicates that Truck drivers reduced their speeds, on the average, by 2.7 mph when they reached the end of the taper; and that this reduction may be attributed to the taper. The observed range of the reductions for 90% of the Trucks was -0.8 to 5.8 mph. However, the speed reduction frequency distribution for IP b shows that 22% of Trucks reduced their speeds less than 1 mph, and 47% reduced less than 2 mph between the beginning and end of the taper. Thus, the remaining 53% significantly influenced the average speed reduction value. Similar arguments can be made for IP c and IP d.

Truck drivers continued reducing their speeds after passing the taper. At the first speed limit signs (IP d), the mean speed reduction was about 3.4 mph, and the reduction fluctuated between 6 and 7 mph until the Trucks reached IP h. At IP h, which is about
<table>
<thead>
<tr>
<th>Influence Points Compared</th>
<th>Average Speed Difference</th>
<th>Standard Deviation</th>
<th>Standard Error</th>
<th>Confidence Level Speeds Are Different</th>
<th>Observed Range for 90% of Speed Changes</th>
</tr>
</thead>
<tbody>
<tr>
<td>(IP b)-(IP a)</td>
<td>-2.7</td>
<td>2.14</td>
<td>0.31</td>
<td>99.99</td>
<td>-5.8 - 0.8</td>
</tr>
<tr>
<td>(IP c)-(IP a)</td>
<td>-2.6</td>
<td>2.47</td>
<td>0.35</td>
<td>99.99</td>
<td>-6.5 - 0.6</td>
</tr>
<tr>
<td>(IP d)-(IP a)</td>
<td>-3.4</td>
<td>2.76</td>
<td>0.39</td>
<td>99.99</td>
<td>-7.3 - 0.6</td>
</tr>
<tr>
<td>(IP e)-(IP a)</td>
<td>-5.6</td>
<td>3.20</td>
<td>0.46</td>
<td>99.99</td>
<td>-10.7 - 1.4</td>
</tr>
<tr>
<td>(IP f)-(IP a)</td>
<td>-7.2</td>
<td>4.22</td>
<td>0.60</td>
<td>99.99</td>
<td>-15.5 - 1.2</td>
</tr>
<tr>
<td>(IP g)-(IP a)</td>
<td>-6.7</td>
<td>4.78</td>
<td>0.68</td>
<td>99.99</td>
<td>-15.2 - 0.3</td>
</tr>
<tr>
<td>(IP h)-(IP a)</td>
<td>-9.8</td>
<td>5.24</td>
<td>0.75</td>
<td>99.99</td>
<td>-18.8 - 2.2</td>
</tr>
<tr>
<td>(IP i)-(IP a)</td>
<td>-11.5</td>
<td>6.03</td>
<td>0.86</td>
<td>99.99</td>
<td>-22.0 - 2.2</td>
</tr>
<tr>
<td>(IP j)-(IP a)</td>
<td>-9.1</td>
<td>6.09</td>
<td>0.87</td>
<td>99.99</td>
<td>-19.2 - 0.3</td>
</tr>
<tr>
<td>(IP k)-(IP a)</td>
<td>-6.7</td>
<td>5.21</td>
<td>0.74</td>
<td>99.99</td>
<td>-14.7 - 0.4</td>
</tr>
<tr>
<td>(IP l)-(IP a)</td>
<td>-6.3</td>
<td>4.69</td>
<td>0.67</td>
<td>99.99</td>
<td>-12.3 - 1.1</td>
</tr>
<tr>
<td>(IP m)-(IP a)</td>
<td>-4.7</td>
<td>5.00</td>
<td>0.71</td>
<td>99.99</td>
<td>-11.9 - 3.1</td>
</tr>
<tr>
<td>(IP h)-(IP j)</td>
<td>-0.7</td>
<td>3.44</td>
<td>0.49</td>
<td>82.55</td>
<td>-4.9 - 5.4</td>
</tr>
<tr>
<td>(IP c)-(IP e)</td>
<td>3.0</td>
<td>2.48</td>
<td>0.35</td>
<td>99.99</td>
<td>-0.1 - 6.5</td>
</tr>
<tr>
<td>(IP d)-(IP m)</td>
<td>1.3</td>
<td>4.24</td>
<td>0.61</td>
<td>96.61</td>
<td>-5.3 - 7.9</td>
</tr>
<tr>
<td>(IP g)-(IP k)</td>
<td>0.01</td>
<td>3.73</td>
<td>0.53</td>
<td>1.58</td>
<td>-6.2 - 6.5</td>
</tr>
</tbody>
</table>
600 ft before the bridge, the reduction increased to 9.8 mph. The largest average speed reduction was 11.5 mph which occurred over the bridge (IP j). The maximum speed reduction at the bridge was 24.3 mph, which also happened at the bridge. The standard deviation of speed differences increased as Trucks approached the work space, and the largest ones (6.03 mph and 6.09 mph) occurred at IP i and IP j.

After passing the bridge, the speed reductions became smaller as drivers traveled further away from the bridge. That means the Trucks increased their speeds after passing the work space. The variance of the speed differences reached its maximum value at IP j. It should be noted that the reductions on either side of the bridge are very similar, indicating that after passing the bridge the drivers almost reached the speed they had before the bridge.

Reductions Compared to Other Points

Further comparisons were made between pairs of IPs to assess the reductions at selected points. The first pair to be considered were the points 600 ft before and 500 ft after the bridge (IP h vs IP j). For this pair, the speed difference for Trucks was 0.7 mph indicating that the average speed of Trucks at 600 ft before the bridge was not significantly different than that at 500 ft after the bridge. This means that the drivers reduced their speed over the bridge, but increased it to the same level as before the work space.

The second comparison pair considered the points 500 ft before and 500 ft after the first speed limit signs (IP c vs IP e). The mean speed reduction for this pair was 3.0 mph, which is a significant amount. This means that on the average the speed was reduced 3.0 mph around the first speed limit signs. Assuming that at 500 ft before the first speed limit signs the drivers had reached their desired speed, the mean speed difference of 3.0 mph is mainly caused by the speed limit signs. It should be noted that a portion of this reduction perhaps is due to the upgrade segment on the highway, but that portion can not be determined from the available data. Thus, considering the upgrade effect, it can be concluded that the Trucks on the average reduced their speeds by less than 3 mph immediately after passing the speed limit signs.

The third pair of comparisons was between IP d and IP m, where the first speed limit signs and the second speed limit signs were located. The difference in reductions between these two Influence Points was 1.3 mph, which was not significant. This indicates although the Trucks reduced their speeds over the bridge, by the time they reached IP m they increased their speeds to the speed level they had at IP d.

The last comparison pair was IP g and IP k (1,200 ft before and 1,000 ft after the bridge). The reduction difference between them was 0.01 mph. This indicates that after traveling about 1,000 ft vehicles attempted to reach the speed they had 1,200 ft before the bridge.

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Normality Test for Autos and Trucks

As mentioned before, not all of the speed reduction distributions were bell-shaped. The distributions around the bridge are closer to a normal distribution than the others. Statistical tests are needed to determine which distributions are normal. The method used here is the Shapiro-Wilk's statistic for normality testing (15). In this method, the Shapiro-Wilk statistic, W, which is the ratio of the best estimator of the variance (based on the square of a linear combination of the order statistics) to the usual corrected sum of squares estimator of the variance is computed. W must be greater than zero and less than or equal to one. Smaller values of W lead to rejection of the null hypothesis that the distributions are normal (15).

The normality test results for the distributions shown in Figures 4.2 through 4.13 are summarized in Table 4.3. Speed reduction distributions for Autos are not normally distributed with a 90% confidence level. Similarly, the speed reduction distributions for Trucks are not normally distributed except at four locations near the bridge. These four IP are located at 1200 ft, 600 ft before the bridge and 500 ft, 1000 ft after the bridge.

Table 4.3. Normality test result based on 90% confidence level

<table>
<thead>
<tr>
<th>Influence Point</th>
<th>Auto</th>
<th></th>
<th>Truck</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Prob&lt;W</td>
<td>Normal</td>
<td>Prob&lt;W</td>
<td>Normal</td>
</tr>
<tr>
<td>IP b</td>
<td>0.0001</td>
<td>No</td>
<td>0.0001</td>
<td>No</td>
</tr>
<tr>
<td>IP c</td>
<td>0.0001</td>
<td>No</td>
<td>0.0001</td>
<td>No</td>
</tr>
<tr>
<td>IP d</td>
<td>0.0001</td>
<td>No</td>
<td>0.0179</td>
<td>No</td>
</tr>
<tr>
<td>IP e</td>
<td>0.0001</td>
<td>No</td>
<td>0.005</td>
<td>No</td>
</tr>
<tr>
<td>IP f</td>
<td>0.0184</td>
<td>No</td>
<td>0.0068</td>
<td>No</td>
</tr>
<tr>
<td>IP g</td>
<td>0.0393</td>
<td>No</td>
<td>0.1875</td>
<td>Yes</td>
</tr>
<tr>
<td>IP h</td>
<td>0.0098</td>
<td>No</td>
<td>0.2799</td>
<td>Yes</td>
</tr>
<tr>
<td>IP i</td>
<td>0.0006</td>
<td>No</td>
<td>0.0857</td>
<td>No</td>
</tr>
<tr>
<td>IP j</td>
<td>0.0001</td>
<td>No</td>
<td>0.3254</td>
<td>Yes</td>
</tr>
<tr>
<td>IP k</td>
<td>0.0001</td>
<td>No</td>
<td>0.7761</td>
<td>Yes</td>
</tr>
<tr>
<td>IP l</td>
<td>0.0905</td>
<td>No</td>
<td>0.0313</td>
<td>No</td>
</tr>
<tr>
<td>IP m</td>
<td>0.0735</td>
<td>No</td>
<td>0.0549</td>
<td>No</td>
</tr>
</tbody>
</table>
5. EFFECTS OF INITIAL SPEED IN SPEED REDUCTION

Drivers travel at different speeds at the beginning of the lane closure taper, and their initial speeds may influence the speeds they will maintain in the work zone. In this part of the report it is attempted to determine how the initial speed of a vehicle would influence its speed in the work activity area. In other words, what would the effects of the speeds at the beginning of the lane closure taper be on the speeds inside the one-lane section of the work zone?

The speeds at the beginning of the taper are used to group the vehicles into four speed groups: Fast, Faster, Very Fast, and Fastest moving groups. The drivers in the Fast group had speeds between 46 and 54 mph when they passed IP a (beginning of the taper). This means that the drivers in the Fast group drove 1 to 9 mph over the speed limit of 45 mph. The drivers in the Faster group had initial speeds of 55 to 64 mph; thus, their speeds were 10 to 19 mph faster than the speed limit. The Very Fast group had initial speeds of 65 to 69 mph. The Fastest group includes all the drivers who had a speed of 70 mph or greater at the beginning of the taper (IP a). The number of vehicles in each group is given in Table 5.1. Since Truck drivers and Auto drivers had slightly different speed distributions, their speed characteristics are studied separately.

Table 5.1 Speed groups and number of vehicles in each group

<table>
<thead>
<tr>
<th>SPEED GROUP</th>
<th>INITIAL SPEED</th>
<th>VEHICLE TYPE</th>
<th>NO. OF VEH.</th>
</tr>
</thead>
<tbody>
<tr>
<td>FAST</td>
<td>46 - 54</td>
<td>Autos</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Trucks</td>
<td>12</td>
</tr>
<tr>
<td>FASTER</td>
<td>55 - 64</td>
<td>Autos</td>
<td>33</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Trucks</td>
<td>34</td>
</tr>
<tr>
<td>VERY FAST</td>
<td>65 - 69</td>
<td>Autos</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Trucks</td>
<td>3</td>
</tr>
<tr>
<td>FASTEST</td>
<td>&gt;= 70</td>
<td>Autos</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Trucks</td>
<td>0</td>
</tr>
</tbody>
</table>

Comparison of Auto Speed Groups

In general, all Auto groups exceeded the 45 mph speed limit, but different speed groups had similar speed reduction trends. As
shown in Figure 5.1, the average speeds gradually decreased before the bridge (IP i) and increased after that for all four speed groups. The average, minimum, and maximum amount the vehicles exceeded the speed limit at different Influence Points are given in Table 5.2. The numbers in the table show the extent the four different speed groups exceeded the 45 mph speed limit at each Influence Point. The average values of the excessive speeds for the four speed groups are shown in Figure 5.1.

![Figure 5.1](image)

Furthermore, for each speed group, the maximum speed reduction was determined by subtracting the lowest mean speed from the initial mean speed. For example, the Fastest group exceeded the speed limit by 26.5 mph at the beginning of the taper (IP a), and by 9.8 mph at the bridge; so, the maximum speed reduction for this group was 16.7 mph. The maximum reductions for Fast, Faster, Very Fast, and Fastest moving groups were 10.5, 10.6, 15.8, and 16.7 mph, respectively.

The maximum speed reduction increased as the initial mean speeds increased. This trend indicates that, on the average, the vehicles with higher speeds at IP a reduced their speeds more than the vehicles with a lower initial speed.

The drivers in the higher initial speed groups kept higher speeds in the work zone than the drivers in the lower initial speed groups, even though the former group had larger speed reduction than the latter group. The Very Fast group exceeded the speed limit by 6 to 22 mph, although they had a maximum speed reduction.
Table 5.2. Speeds in excess of 45 mph for different Auto speed groups

<table>
<thead>
<tr>
<th>Influence Point</th>
<th>Fast Group</th>
<th>Faster Group</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min</td>
<td>Max</td>
</tr>
<tr>
<td>a</td>
<td>1.1</td>
<td>9.0</td>
</tr>
<tr>
<td>b</td>
<td>-1.3</td>
<td>6.6</td>
</tr>
<tr>
<td>c</td>
<td>-0.2</td>
<td>7.2</td>
</tr>
<tr>
<td>d</td>
<td>-3.3</td>
<td>6.4</td>
</tr>
<tr>
<td>e</td>
<td>-2.2</td>
<td>4.3</td>
</tr>
<tr>
<td>f</td>
<td>-1.5</td>
<td>7.4</td>
</tr>
<tr>
<td>g</td>
<td>0.1</td>
<td>8.4</td>
</tr>
<tr>
<td>h</td>
<td>-9.7</td>
<td>5.3</td>
</tr>
<tr>
<td>i</td>
<td>-13.4</td>
<td>5.4</td>
</tr>
<tr>
<td>j</td>
<td>-11.4</td>
<td>4.4</td>
</tr>
<tr>
<td>k</td>
<td>-3.8</td>
<td>8.7</td>
</tr>
<tr>
<td>l</td>
<td>-0.4</td>
<td>12.0</td>
</tr>
<tr>
<td>m</td>
<td>-3.2</td>
<td>14.7</td>
</tr>
</tbody>
</table>

Sta. Dev = Standard Deviation
Table 5.2. Speeds in excess of 45 mph for different Auto speed groups (continued)

<table>
<thead>
<tr>
<th>Influence Point</th>
<th>Very Fast Group</th>
<th></th>
<th></th>
<th>Fastest Group</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min</td>
<td>Max</td>
<td>Mean</td>
<td>Sta.Dev</td>
<td>Min</td>
</tr>
<tr>
<td>a</td>
<td>19.6</td>
<td>24.3</td>
<td>21.5</td>
<td>1.56</td>
<td>24.7</td>
</tr>
<tr>
<td>b</td>
<td>9.7</td>
<td>23.1</td>
<td>18.9</td>
<td>3.11</td>
<td>17.2</td>
</tr>
<tr>
<td>c</td>
<td>7.7</td>
<td>23.8</td>
<td>17.4</td>
<td>4.05</td>
<td>14.4</td>
</tr>
<tr>
<td>d</td>
<td>0.9</td>
<td>23.4</td>
<td>15.0</td>
<td>5.08</td>
<td>12.5</td>
</tr>
<tr>
<td>e</td>
<td>-0.4</td>
<td>20.8</td>
<td>13.0</td>
<td>5.58</td>
<td>6.4</td>
</tr>
<tr>
<td>f</td>
<td>-2.3</td>
<td>24.7</td>
<td>13.5</td>
<td>6.70</td>
<td>5.9</td>
</tr>
<tr>
<td>g</td>
<td>-2.0</td>
<td>26.0</td>
<td>14.3</td>
<td>6.68</td>
<td>9.1</td>
</tr>
<tr>
<td>h</td>
<td>-10.6</td>
<td>22.3</td>
<td>8.8</td>
<td>7.41</td>
<td>-2.7</td>
</tr>
<tr>
<td>i</td>
<td>-20.2</td>
<td>22.2</td>
<td>5.7</td>
<td>9.64</td>
<td>-7.0</td>
</tr>
<tr>
<td>j</td>
<td>-6.8</td>
<td>23.1</td>
<td>9.9</td>
<td>7.29</td>
<td>-12.1</td>
</tr>
<tr>
<td>k</td>
<td>4.6</td>
<td>23.7</td>
<td>14.0</td>
<td>4.43</td>
<td>0.7</td>
</tr>
<tr>
<td>l</td>
<td>4.3</td>
<td>24.3</td>
<td>14.7</td>
<td>4.25</td>
<td>7.2</td>
</tr>
<tr>
<td>m</td>
<td>3.3</td>
<td>27.8</td>
<td>15.4</td>
<td>5.53</td>
<td>8.7</td>
</tr>
</tbody>
</table>

Sta. Dev = Standard Deviation
of 15.8 mph. In comparison, the Fast group exceeded the speed limit only by 5 mph and traveled 5 mph below the speed limit at the bridge, but had a maximum speed reduction of 10.5 mph, which is smaller than 15.8 mph for the Very Fast group.

Comparison of Truck Speed Groups

Truck speeds were more concentrated near the mean speed and were relatively lower than the Autos'; thus, Trucks had only Fast, Faster and Very Fast groups. There were no trucks with speeds greater than 70 mph. The criteria for classification of the Trucks was the same as that for the Autos. It should be noted that, the Very Fast group had a very small sample size (there were only three trucks in the Very Fast group); thus, this group is not discussed in detail.

The speed characteristics for the Trucks in the three speed groups at different Influence Points are given in Table 5.3. All Truck groups exceeded the 45 mph speed limit at all IPs, except the Fast group which had lower speeds at IPs h and i (see Figure 5.2). The curves in the figure indicate that different speed groups had very similar speed reduction trends. For all speed groups, the average speed gradually decreased before the bridge (IP i) and increased after the bridge.

Figure 5.2
Profile of speeds for trucks grouped by initial speeds

<table>
<thead>
<tr>
<th>Speed in excess of 45 mph</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very Fast Group</td>
</tr>
<tr>
<td>Faster Group</td>
</tr>
<tr>
<td>Fast Group</td>
</tr>
</tbody>
</table>

Influence Points and distance (1000 ft)
Table 5.3. Speeds in excess of 45 mph for different truck speed groups

<table>
<thead>
<tr>
<th>Influence Point</th>
<th>Fast Group</th>
<th>Faster Group</th>
<th>Very Fast Group</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min</td>
<td>Max</td>
<td>Mean</td>
</tr>
<tr>
<td>a</td>
<td>0.5</td>
<td>8.2</td>
<td>5.2</td>
</tr>
<tr>
<td>b</td>
<td>-6.7</td>
<td>7.1</td>
<td>2.2</td>
</tr>
<tr>
<td>c</td>
<td>-6.2</td>
<td>7.9</td>
<td>2.7</td>
</tr>
<tr>
<td>d</td>
<td>-4.8</td>
<td>7.2</td>
<td>2.4</td>
</tr>
<tr>
<td>e</td>
<td>-5.2</td>
<td>7.1</td>
<td>0.9</td>
</tr>
<tr>
<td>f</td>
<td>-7.0</td>
<td>11.</td>
<td>0.7</td>
</tr>
<tr>
<td>g</td>
<td>-8.8</td>
<td>11.</td>
<td>1.2</td>
</tr>
<tr>
<td>h</td>
<td>-11.7</td>
<td>8.2</td>
<td>-1.5</td>
</tr>
<tr>
<td>i</td>
<td>-9.7</td>
<td>7.0</td>
<td>-2.2</td>
</tr>
<tr>
<td>j</td>
<td>-4.5</td>
<td>10.</td>
<td>0.4</td>
</tr>
<tr>
<td>k</td>
<td>-1.5</td>
<td>11.</td>
<td>2.0</td>
</tr>
<tr>
<td>l</td>
<td>-0.3</td>
<td>8.8</td>
<td>1.9</td>
</tr>
<tr>
<td>m</td>
<td>0.8</td>
<td>9.2</td>
<td>3.3</td>
</tr>
</tbody>
</table>

S.D. = Standard Deviation
Comparing the lowest mean speed with the initial mean speed, the maximum speed reduction for each speed group was determined. For example, the Faster group exceeded the speed limit by 13.43 mph at the beginning of the taper (IP a), and by 1.25 mph at the bridge; so, the maximum speed reduction for this group was 12.18 mph. The maximum reduction for Fast moving groups was 7.44 mph.

The maximum speed reduction increased as the initial average speeds increased. This trend indicates that, on the average, the vehicles with higher speeds at IP a reduced their speeds more than the vehicles with lower speed. However, the drivers in the higher initial speed groups kept higher speeds in the work zone than the drivers in the lower initial speed groups, even though the former group had larger speed reductions than the latter group.

The trucks in the Faster group exceeded the speed limit by 1 to 13 mph, although they had a maximum speed reduction of 12.18 mph. In comparison, the Fast group exceeded the speed limit only by 5 mph at the beginning and traveled 2 mph below the speed limit at the bridge, but had maximum speed reduction of 7.44 mph.
6. CONCLUSIONS AND RECOMMENDATIONS

Conclusions

This study determined the speed profile of vehicles as they traveled through a 1.5-mile long section of a work zone. At different locations within the work zone, most of the motorists changed their speeds in response to roadway geometry and traffic control devices. The speed reduction profile of each vehicle was obtained from the speed profiles. The findings of this study are reported in the following four sections.

Speed Characteristics

The average speeds of Autos and Trucks were 5-18 mph and 1-12 mph, respectively, over the work zone speed limit. The average speeds of Autos were about 4-7 mph higher than those of Trucks. Auto and Truck drivers decreased their speeds to the lowest level near the work space, but after passing it they increased their speeds to the higher levels they had before the work space.

The percentage of vehicles exceeding a speed level decreased as they approached the work space (bridge), but after passing it the percentage increased to the higher levels found before the work space. Although the percentage of vehicles exceeding the speed limit at the work space was the lowest compared to other locations, nearly 65% of Autos and 47% of Trucks traveled faster than 45 mph at this location.

Drivers Categories

Four categories of drivers were identified based on the speed reduction profiles. The drivers in different categories showed distinct speed reduction patterns. The speed profiles for Autos and Trucks indicated that they have similar speed reduction patterns in the work zone. About 61% of the drivers reduced their speeds considerably after passing the first work zone speed limit signs, which were located at the beginning of the one-lane section of the work zone (These drivers comprised Category 1).

Category 1 was further divided into three sub-categories. Approximately 24% of the drivers were in Category 1.1, which represents the drivers who decreased their speeds near the first work zone speed limit signs and had further speed reductions at the work space (bridge). The latter speed reduction often was greater than the former reduction. About 22% of the drivers slowed down considerably at the first speed limit signs and at the bridge, but between these two points increased their speeds (Category 1.2). Their speed profiles resembled a "W". Nearly 15% of the drivers reduced their speed around the first speed limit signs and kept traveling at that reduced speed until they passed the bridge.
(Category 1.3). Categories 2-4 included 39% of the drivers. Nearly 15% of the drivers did not reduce their speeds until they neared the location of construction activities (Category 2). About 11% of the drivers traveled at constant high speeds and did not reduce their speeds considerably in the work zone (Category 3). The profiles for the remaining drivers did not indicate a common pattern (Category 4).

The proportions of Trucks and Autos in the driver categories were similar except in Categories 1.3 and 2. The percentage of Truck drivers who reduced their speeds around the first speed limit signs and kept traveling at that reduced speed until they passed the bridge (Category 1.3) was twice that of the Auto drivers. However, the percentage of Truck drivers who traveled faster than the speed limit and basically ignored the first speed limit sign, but began to slow down when they arrived at the work space (Category 2) was about one half of the percentage of Auto drivers. Thus, appropriate counter measures to increase speed compliance in work zones should mainly be directed to the intended category of drivers.

**Speed Reductions**

Autos and Trucks, on the average, traveled 3-13 mph and 3-12 mph, respectively, slower inside the work zone compared to the their speeds at the beginning of the taper. As drivers traveled further into the work zone the speed reductions first increased, then slightly decreased, and finally reached a maximum value at the bridge. After passing the bridge, the speed reductions continuously decreased until vehicles left the study section. It is important to note that a small percentage of drivers reduced their speeds large amounts; thus, the speed reduction frequency distribution plots were not bell-shaped, but had a long tail. These shapes must be considered in making statistical inferences.

Comparisons of speed reductions at different locations before the work space to the reductions at similar locations past the work space indicated that vehicles attempted to reach the speeds they had before the bridge. The speed reductions before and after the first work zone speed limit signs were also compared. The speed limit signs were found to be effective in reducing the average speed of Autos by 3.5 mph, and that of Trucks by less than 3 mph, at a point immediately after the signs.

**Speed Groups**

The speeds at the beginning of the taper were used to group the vehicles into four speed groups: Fast, Faster, Very Fast, and Fastest moving group. For all speed groups, the average speeds gradually decreased before the bridge and increased after passing the bridge. The maximum reduction in the average speed at different locations increased as the initial mean speeds increased. This
trend indicates that, on the average, the vehicles with higher speeds at the beginning of the taper reduced their speeds more than the vehicles with lower initial speeds. However, the drivers in the higher initial speed groups kept higher speeds in the work zone than the drivers in the lower initial speed groups, even though the former group had larger speed reductions than the latter group.

Recommendations

The location at which drivers slow down, or speed up, are critical points in a construction zone. Knowing these points would help to place the signs at their appropriate locations. It is recommended that the placement and frequency of the work zone speed limit signs be examined using the speed reduction pattern of the vehicles. The measures taken to slow down the drivers in Category 3 who ignored the speed limit signs and the construction activities may be different from those for drivers in Category 1.

Category 1.3 is an ideal pattern and other drivers should be encouraged to follow this pattern. Placing additional speed limit signs between the first speed limit signs and the work space may persuade the drivers in Category 1.1 to slow down further, and may discourage the drivers in Category 1.2 from increasing their speed before the work space. The drivers in Category 1.2 may have increased their speeds because they perceived that the work space was too far from the first speed limit signs.

The location of the signs and the length of the section before the work space should be such that most drivers are encouraged to follow the speed limit. Since 61% of drivers reduced their speeds around the first speed limit signs and 75% of all drivers reduced their speeds near the work space, more speed reduction may be achieved if the work space is closer to the beginning of the work zone.

The analysis indicated that location of a speed measuring station has to be carefully selected because it will affect the outcome of the measurements. Furthermore, speed distributions, as well as the mean speeds, should be analyzed in order to obtain more accurate speed characteristic data. Speed profile data from other work zones should be used to further validate the findings of this study.

The data reduction stage should be computerized to reduce the human resources needed. The video images provide a permanent record that will reduce the mistakes caused by human or equipment error. The computational errors of this data collection method are reasonable. This approach, though time consuming in the data reduction stage, should be used in future studies.
REFERENCES


APPENDIX A.

DATA REDUCTION PROCEDURE
Data reduction took a long time and required a lot of manpower. The data reduction process needs to automated and computerized. Five of the steps discussed here involved: 1) Finding travel times, 2) Finding travel distances, 3) Computing speed in highway intervals, 4) Finding speeds at the markers, and 5) Computing speeds at the overlapping intervals. Other steps such as determining speeds at the Influence Points, and error checking are discussed elsewhere in this report. In the following sections Items 1 through 5 and comparison of speed of cars to vans will be discussed.

Travel Times

The time at which a vehicle passed a marker was recorded to the accuracy of 1/30 of a second. To obtain this accuracy the frame numbers of the video images were recorded (burned in) on the video tapes. Every 30 frames amounted to 1 second. From the recorded data the time a vehicle spent between two markers was computed. On the average a vehicle took about 1.5-2 minutes to travel the study section. For each vehicle at least 21 readings of the time were recorded from the video tapes.

For a very small number of autos the time a vehicle passed a marker was not always available because the view was blocked by the vehicles traveling on DeWitt Road or Route 16. The missing data points were computed using the supplementary markers. When such a supplementary marker was not available, an imaginary marker was established using the foreground and the background views of the location on the TV monitor.

Travel Distances

The distance between two markers as an observer sees it on the TV monitor is not equal to the actual longitudinal distance between the markers along the highway. The distance a vehicle traveled during the two readings of the time was the distance subtended between the lines connecting the markers to the camera location. The traveled distance is computed using the lateral distances from the markers to the travel path of the vehicle and the angles between the road and the lines from the markers to the camera location. An example of the distance computations is given in Figure A.1. The actual longitudinal distances between the markers were measured using a measuring tape.

Speed at Highway Intervals

For each vehicle the average speed between two markers was computed by knowing the time and the traveled distance. Based on the data that was collected from Camera Location 1, the speeds for 9 highway intervals were computed. Similarly, the speeds were
Figure A.1 Travel distance computation between markers A and B

\[ \tan a_1 = \frac{d_1}{L_1 + L_2 + L_3} \]

\[ \tan a_2 = \frac{d_2}{R_3} \]

\[ d = (d_2 - d_1) + (L_1 + L_2) \tan a_1 + (R_1 + R_2) \tan a_2 \]
computed for 10 highway intervals from the data collected at Camera Location 2. The speeds on the two overlapping intervals were computed using the data from both camera locations.

**Speed at the Markers**

A map of the study area was drawn with a scale of 1 inch equal to 100 ft. A line of sight from a camera location to a marker was extended to cross the southbound lanes of the highway. By doing this, it was possible to determine the location of the vehicle on the lanes at the time that it appeared to pass the marker. These lines divided the study section along the highway into smaller intervals. The length of each interval is equal to the distance a vehicle traveled between the two markers as seen from the camera locations.

The speeds computed in the previous section are for these intervals. The speeds were assumed to correspond to the speeds at or near (100 ft) the midpoints of the intervals. Using the computed speeds and the map, speed of a vehicle at any point on the highway could be determined. The length of each interval and the X coordinate of its midpoint are given in Table A.1.

**Speed at Overlapping Intervals**

There were 2 overlapping intervals in the middle of the study section. The intervals were from the DeWitt Road Abutment to Double-cross Pole, and from the Double-cross Pole to the Overhead Sign/Light post. Speeds of vehicles on the overlapping intervals were computed by both teams. The speeds computed by the two teams were very close. For most of the computations the differences were less than 1 mph. Thus, it was decided to use the average of the two speeds as the speed on the corresponding overlapping interval.

It should be noted that the midpoints of the overlapping intervals as seen from Camera Location 1 do not correspond to the midpoints from Camera Location 2. The midpoints were about 100-200 ft apart. The coverage from each camera location was examined to select the appropriate midpoint. Consequently, for the first overlapping interval, the midpoint of the segment for the Camera Location 2 was used. However, for the second overlapping interval, where the midpoints were 200 ft apart, a point between the two midpoints was selected.

**Comparison of Speed of Cars to Speed of Vans**

The speed characteristics of the cars were compared to those of the vans to determine whether there were significant differences for the two vehicle types. Table A.2 shows the results of the comparison between these two groups. The hypothesis used in this test is that there is not a significant difference between the mean speed of cars and vans at a given influence point. The confidence
Table A.1. Length and X coordinate of the midpoint of the interval subtended by markers

<table>
<thead>
<tr>
<th>LOCATION OF MARKERS</th>
<th>INTERVAL LENGTH (FT)</th>
<th>MIDPOINT COORDINATE (FT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MARKERS SEEN FROM CAMERA LOCATION 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>65 mph Speed Sign</td>
<td>-</td>
<td>200</td>
</tr>
<tr>
<td>End of Construction</td>
<td>162.00</td>
<td>600</td>
</tr>
<tr>
<td>Flashing Arrow</td>
<td>525.07</td>
<td>1100</td>
</tr>
<tr>
<td>Hospital Sign</td>
<td>425.32</td>
<td>1600</td>
</tr>
<tr>
<td>Tree Marker</td>
<td>529.39</td>
<td>2100</td>
</tr>
<tr>
<td>First 45 mph Signs</td>
<td>615.45</td>
<td>2600</td>
</tr>
<tr>
<td>Guardrail Marker</td>
<td>334.35</td>
<td>3100</td>
</tr>
<tr>
<td>DeWitt Abutment</td>
<td>540.36</td>
<td>3700</td>
</tr>
<tr>
<td>Double-cross Pole</td>
<td>754.51</td>
<td>4300</td>
</tr>
<tr>
<td>Overhead Sign/Light Post</td>
<td>606.65</td>
<td>4800</td>
</tr>
<tr>
<td>MARKERS SEEN FROM CAMERA LOCATION 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DeWitt N. Abutment</td>
<td>-</td>
<td>3700</td>
</tr>
<tr>
<td>Double-cross Pole</td>
<td>656.79</td>
<td>4300</td>
</tr>
<tr>
<td>Overhead Sign/Light Post</td>
<td>712.77</td>
<td>4800</td>
</tr>
<tr>
<td>Merge Sign</td>
<td>454.55</td>
<td>5400</td>
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<tr>
<td>First Light Post</td>
<td>720.27</td>
<td>6000</td>
</tr>
<tr>
<td>Second Light Post</td>
<td>414.11</td>
<td>6500</td>
</tr>
<tr>
<td>Ramp Marker</td>
<td>519.28</td>
<td>7000</td>
</tr>
<tr>
<td>Overhead Sign</td>
<td>624.93</td>
<td>7500</td>
</tr>
<tr>
<td>Box Marker</td>
<td>372.53</td>
<td>7900</td>
</tr>
<tr>
<td>Second 45 mph Signs</td>
<td>467.80</td>
<td>8300</td>
</tr>
<tr>
<td>Coles County Sign</td>
<td>259.72</td>
<td>-</td>
</tr>
</tbody>
</table>

level used to reject the hypothesis is 95%, i.e. α = 0.05.

The results of the comparisons indicated that cars and vans had very similar speed characteristics. At Influence Point a, for instance, the average speed of passenger cars was 62.6 mph and the average speed of vans was 64 mph. Based on the results of the t-test, one can state that the mean speed of cars was different than the mean speed of vans only with a confidence level of 64.09%. This confidence level is too low to conclude that the speeds were different. With a higher confidence level the speeds cannot be considered different. When 95% confidence level is used, speeds of the cars and vans were not significantly different. As indicated
Table A.2 Comparison of the mean speeds and speed variances for cars and vans at different Influence Points

<table>
<thead>
<tr>
<th>Influence Point</th>
<th>cars</th>
<th>vans</th>
<th>Confidence level the mean speeds are different %</th>
<th>Are mean speeds the same with 95% confidence level</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>62.6</td>
<td>64</td>
<td>64.09</td>
<td>Yes</td>
</tr>
<tr>
<td>b</td>
<td>59.8</td>
<td>61.9</td>
<td>82.43</td>
<td>Yes</td>
</tr>
<tr>
<td>c</td>
<td>58.9</td>
<td>61.9</td>
<td>93.45</td>
<td>Yes</td>
</tr>
<tr>
<td>d</td>
<td>57.2</td>
<td>59.4</td>
<td>83.56</td>
<td>Yes</td>
</tr>
<tr>
<td>e</td>
<td>55.6</td>
<td>57.5</td>
<td>79.09</td>
<td>Yes</td>
</tr>
<tr>
<td>f</td>
<td>56</td>
<td>57.2</td>
<td>54.62</td>
<td>Yes</td>
</tr>
<tr>
<td>g</td>
<td>56.8</td>
<td>57.5</td>
<td>30.43</td>
<td>Yes</td>
</tr>
<tr>
<td>h</td>
<td>52.2</td>
<td>53.3</td>
<td>42.82</td>
<td>Yes</td>
</tr>
<tr>
<td>i</td>
<td>49.3</td>
<td>50.2</td>
<td>31.19</td>
<td>Yes</td>
</tr>
<tr>
<td>j</td>
<td>52.2</td>
<td>53</td>
<td>33.18</td>
<td>Yes</td>
</tr>
<tr>
<td>k</td>
<td>56.11</td>
<td>56.4</td>
<td>16.06</td>
<td>Yes</td>
</tr>
<tr>
<td>l</td>
<td>56.9</td>
<td>57.36</td>
<td>26.88</td>
<td>Yes</td>
</tr>
<tr>
<td>m</td>
<td>56.9</td>
<td>58.6</td>
<td>74.04</td>
<td>Yes</td>
</tr>
</tbody>
</table>
in Table A.2, there was not a significant difference between the mean speeds of cars and vans at all influence points. Thus, the cars and vans were combined into one group which is called Auto group.
APPENDIX B.

ERROR CHECKING
APPENDIX B. ERROR CHECKING

Introduction

Two categories of errors were checked: Noticeable errors and computational errors. The common sources of the noticeable errors could be: Mistakes in computing time or distance, input errors, or errors due to missing data. The speed profile of each vehicle was reviewed to check whether there were any noticeable errors (e.g. a sudden increase or decrease in speed). Possible sources of noticeable errors were identified and corrected.

The computational errors are due to the procedures used to calculate speeds of vehicles. The computational errors and sensitivity of the computed speed to the input values were examined. The computational errors could come from sources such as: Error in computing the travel time, errors due to the width of vehicle (e.g. car vs truck), errors due to the vehicle's location in the lane, errors in measuring the longitudinal distance between the markers, or lateral distance between the markers and the highway. The magnitude of the computational errors was determined as discussed in the following sections.

Error in Computing Travel Time

An error in travel time may occur when the video tapes were viewed to record the time a vehicle passed a given marker. The time a certain point of a vehicle (e.g. front bumper or fender) passed a marker was recorded to the accuracy of 1/30 of a second (accuracy was 1 frame). From the time readings at two successive markers, the travel time for a vehicle between the two markers was determined. Often it was clear when the vehicle exactly passed the marker, but at times it was not very clear. Thus, there was a chance of making 1/30 of a second judgmental error in reading this time.

The error in time reading would directly cause an error in speed. The magnitude of the speed error would increase when a vehicle is traveling fast and the distance between the markers is short. The shortest distance between the markers was 259.72 and the fastest observed speed in that interval was 72.77 mph. For this condition, an error of 1/30 second would cause a maximum speed error of 0.98 mph. The computations are given below.

Let

\[ s = \frac{d}{t} \]

be the correct speed, and

\[ s' = \frac{d}{(t + \frac{1}{30})} \]

be the speed with 1 frame error. So, the speed error caused would be:
\[ s - s' = d/t - d/t(1/30) \]
\[ = s(1/(30t+1)) \]
\[ = s^2/(30d + s). \]

When \( s = 72.77 \) mph or \( 106.73 \) ft/sec, and \( d = 259.72 \) ft, the error would be \( 1.44 \) ft/sec = \( 0.98 \) mph.

It should be noted that, the above travel time error is computed based on the worst case scenario. The error that could happen on this interval of the highway would be less than \( 0.98 \) because the time reading error was less than \( 1/30 \) second.

**Error Due to Vehicle Width**

It was assumed that cars would be \( 6 \) ft wide and trucks would be \( 8.5 \) ft wide. This width difference would cause some errors because the wider vehicle would seem to spend less time than the narrow vehicle to traverse the subtended distance between the two road markers. Figure B.1 shows the effect of the width on speed computation assuming a \( 12 \) ft traveled lanes.

Let:

\[ \tan (b1) = d1/L1 \]
\[ \tan (b2) = (d1+d2)/(L3+L4+L5). \]

Distance computed based on truck width:
\[ Dt = d2-\tan(b1)*(L2+L4/2+1.75)-\tan(b2)*(L5+10.25). \]

Distance computed based on car width:
\[ Dc = d2-\tan(b1)*(L2+L4/2+3.0)-\tan(b2)*(L5+9.0). \]

The difference between \( Dt \) and \( Dc \) is:
\[ D = Dc - Dt = 1.25 [\tan(b2) - \tan(b1)]. \]

Assume
\[ d \] is the distance between markers,
\[ s = Dc/d \] is the correct speed, and
\[ s' = Dt/d \] is the speed with vehicle width error.

The speed error is:
\[ (s - s'/s = D/d \]
\[ s - s' = 1.25 s * [\tan (b2) - \tan (b1)] / d. \]

In the overlapping intervals, the error computation equation is the same as the non-overlapping intervals (see Figure B.2). The maximum error (the worst case scenario) would happen when speed and the \( D/d \) ratio have their highest values. The maximum \( D/d \) ratio is \( 0.000605 \) and the highest speed in the study section was \( 77.27 \) mph, so, the maximum speed error is \( 0.06 \) mph.
Figure B.1 Error due to vehicle width (truck vs car) in non-overlapping section
Figure B.2 Error due to vehicle width (truck vs car) in overlapping section
Error Due to Vehicle Location

It was assumed that the vehicles would travel in the middle of the traveled lane. This means that the lateral distances between the edge line and one side of a vehicle is assumed to be equal to the distance between the lane line and the other side of the vehicle. When a 6-foot wide vehicle is traveling in the middle of a 12-foot lane, there remains a three-foot margin on each side of the vehicle along the traveled lane. When this assumption is violated, an error in computing speed would occur.

In real world conditions, drivers would travel with some lateral movements within a lane. Figure B.3 illustrates how the lateral movement of a vehicle between two markers would affect the computed speed. For example, at one marker a vehicle may be at position A and when it reaches the next marker, the vehicle might be at position B. There are a total of nine possible cases of error that may occur due to the lateral movement (i.e A to A, A to B, A to C, etc., see Figure B.3). Here only the worst case which going from position C at one marker to position C at the other marker will be discussed.

Let:
\[ s = \frac{d}{t} \] be the correct speed, and
\[ s' = \frac{d'}{t} \] be the speed with error
\[ w = \text{one half of the total lateral movement} \]

By definition, the error in speed due to lateral movement would be \( s-s' \). Based on Figure B.3, one can write

\[
\frac{s-s'}{s} = \frac{d'-d}{d} = w*\left[\tan(a1) + \tan(a2)\right]/d
\]

so, the speed error

\[
s-s' = w*s*(\tan(a1) + \tan(a2))/d = w*s*R.
\]

where R is called geometric ratio.

The largest error would happened in an interval that has the largest geometric ratio and maximum speed (i.e largest \( s*R \)). In this study the largest geometric ratio would occur in the interval between the last two markers seen from Camera Location 2. For that interval the values to compute R are:

\[ \tan(a1) = 1.2694, \]
\[ \tan(a2) = 1.4265, \] and
\[ d = 259.72 \text{ feet}. \]

Thus, the geometric ratio is

\[ R = 0.01038, \]
Figure B.3 Error due to lateral location of the vehicle in a lane
The maximum speed in that interval, was \( s = 72.77 \) mph. So, the error due to combination of speed and geometric ratio is

\[
s*R = 72.77 \times 0.01038 \\
= 0.7554
\]

The extreme case would happen when a vehicle moves from one edge of pavement at one marker to the opposite edge at the other marker. That is moving from position C to position C which is a 6 feet lateral movement (Figure B.3). This case is very unlikely to happen, but if it does the error would be:

\[
s-s' = w*s*R \\
= 3 \times 0.7554 \\
= 2.27 \text{ mph.}
\]

Since having a car with combination of the maximum speed and the maximum lateral movement is very rare, errors for three other cases are computed. For these three cases, the average speed in that interval is used instead of the maximum speed. After comparing all combinations of \( s*R \) at all intervals, it was found that the above mentioned interval (last interval seen from Camera Location 2) would still be the critical one. In this interval, the mean speed was 57.4 mph, so

\[
s*R = 57.4 \times 0.01038 \\
= 0.5958
\]

Three lateral shift considered are: a 2 feet lateral shift (w = 1), a 4 feet lateral shift (w = 2 feet), and a 6 feet shift (w=3 feet). The speed errors due to these shift are:

\[
\text{when } w = 1, \quad s-s' = w*s*R \\
= 1 \times 0.5958 \\
= 0.5958 \text{ mph; }
\]

\[
\text{when } w = 2, \quad s-s' = 2 \times 0.5958 \\
= 1.19 \text{ mph; and}
\]

\[
\text{when } w = 3, \quad s-s' = 3 \times 0.5958 \\
= 1.79 \text{ mph.}
\]

A 6 feet or a 4 feet lateral movements is less likely to happen than the smaller shifts. Even when the shift is 4 feet, the speed error is in 1 mph range.

**Tape Measuring Error**

The distances between the markers along the road and the distances from markers to the road were measured using a 165-foot long measuring tape. The error in these measurement would cause some error in speed computation. It was assumed that when the distance was shorter than 165 ft, the measurement error was 2 inches, and when the distance was longer than 165 ft, the error was 2 inches per 165 ft.
Figures B.4 and B.5 are used to compute the measurement error. If \( h_1 \) and \( h_2 \) are on the far side of the highway then they are considered positive, otherwise, they are negative. Based on the above definition above, the following relationships can be written:

\[
\tan (a_1) = \frac{d_1}{h_1 + h} \\
\tan (a_2) = \frac{(d_1 - d_2)}{h + h_2} \\
d = d_2 - h_1 \tan(a_1) + h_2 \tan(a_2) \\
d = d_2 - h_1 \frac{d_1}{h_1 + h} + h_2 \frac{(d_1 - d_2)}{h + h_2}.
\]

The distances due to the tape measurement errors are:

\[
|h_1 - h_1'| \leq 2 \text{ inches or } 1/6 \text{ ft} \\
|h - h'| \leq 2 \text{ inches per 165 ft} \\
|d_1 - d_1'| \leq 2 \text{ inches per 165 ft, and} \\
|d_2 - d_2'| \leq 2 \text{ inches per 165 ft.}
\]

So,

\[
d' = d_2' - h_1' \frac{d_1'}{h_1' + h'} + h_2' \frac{(d_1' - d_2')}{h' + h_2'}
\]

The speed error ratio would be \((s-s')/s = (d-d')/d\). The maximum speed error would be:

\[
\max(s-s') = \max \text{ (speed error ratio)} \times \max \text{ (speed)}.
\]

The worst case error would be 0.44 mph.
Figure B.4  Error due to longitudinal and lateral measurement of distances by a measuring tape on non-overlapping intervals
Figure B.5  Error due to longitudinal and lateral measurement of distances by a measuring tape on overlapping intervals
APPENDIX C.

UPGRADE ADJUSTMENT DATA
APPENDIX C. UPGRADE ADJUSTMENT DATA

Grade Composition

There is an upgrade segment between IP c to IP f. Adjustment data were collected to determine the magnitude of the speed reduction due to the upgrade. The most significant grade is 2.9% which is located between IP d to IP e (from the first speed limit signs to 500 ft after them), which includes 303 feet of 3% uphill section. The grade composition on the study section is shown in Table C.1.

Adjustment Data Collection Site

In order to determine the speed reduction effects of the uphill segment, adjustment data were collected after completion of the construction activities. The site of the adjustment data collection is shown in Figure C.1.

Speeds of a vehicle were recorded at two camera locations. These two camera locations were different from those used in the speed profile study. During the adjustment data collection, one of the cameras was located before the upgrade segment and the other camera near the end of the upgrade. The first camera location was at 500 ft before the 1.7% upgrade and covered the speed between Speed Stations 3 and 4, called Interval 1. Interval 1 represented the vehicle speed on nearly level grade. The second camera location was right at the 1.3% upgrade section, and covered the speed between Speed Stations 7 and 8, called Interval 2. Interval 2 represented the vehicle speed at the end of the upgrade segment. There were two markers in each interval.

Adjustment Data Collection Method

Video images of a vehicle were used to determine its speed. Data were collected at two locations using two video cameras. Both cameras were located on the outside shoulder of the northbound lanes. Each camera covered an interval of the road over 400 ft in length. Each vehicle was video taped at both camera locations. The method used here for taking video images was similar to the one used for the speed profile study.

Adjustment Data Reduction

During data reduction, two TVs were used simultaneously to confirm that the same vehicle was video taped from both camera locations. The times a vehicle passed the two markers at each interval were recorded. Whenever it was suspected that a vehicle was slowed down by another vehicle, the data for the vehicle was discarded. Speeds for 130 cars and 112 trucks were determined.
Table C.1 Grade composition

<table>
<thead>
<tr>
<th>SPEED STATION</th>
<th>IP</th>
<th>DIST. FT</th>
<th>ELEVATION FT.</th>
<th>GRADE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>a</td>
<td>600</td>
<td>691.57</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>1100</td>
<td>693.57</td>
<td>0.4</td>
</tr>
<tr>
<td>3</td>
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<td>695.58</td>
<td>0.4</td>
</tr>
<tr>
<td>4</td>
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<td>697.57</td>
<td>0.4</td>
</tr>
<tr>
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<td>d</td>
<td>2600</td>
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<td>g</td>
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<td>744.55</td>
<td>0.5</td>
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<td>10</td>
<td>h</td>
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<tr>
<td>11</td>
<td>i</td>
<td>6000</td>
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<td>-0.2</td>
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<td>16</td>
<td>m</td>
<td>8300</td>
<td>728.54</td>
<td>-0.3</td>
</tr>
</tbody>
</table>
Figure C.1 Location of adjustment data collection intervals
Speed distributions for cars and trucks indicated that some of the vehicles could be considered outliers because they had an unusual speed increase or decrease, such as a 17 mph increase or a 20 mph decrease. To eliminate the effect of outliers, all the vehicles with more than 11 mph increase or decrease were deleted. The remaining data points, which consisted of 116 cars and 104 trucks, were used for computing the upgrade adjustment.

Analysis Results

Table C.2 shows the speed reductions for cars and trucks due to the upgrade. The mean speed reduction for cars was 1 mph and for trucks it was 4.96 mph. Figures C.2 and C.3 show the speed reduction distributions for cars and trucks. From the Figures, it can be seen that the speed change for most of the cars was concentrated between -1 and 2 mph, and for most of the trucks the concentration was between -3 and -6 mph.

The data indicates that the upgrade section did not significantly reduce the speed of cars, but it did reduce the speed of trucks. The upgrade reduced the average speed of trucks by 5 mph.
Figure C.2
Speed change distribution for cars
at upgrade section

Figure C.3
Speed change distribution for trucks
at upgrade section
APPENDIX D.

SPEED CHARACTERISTICS
APPENDIX D. SPEED CHARACTERISTICS

At each Influence Point (IP), the maximum, minimum, average speed, and standard deviation were computed. These statistics were summarized in Table 3.1. For Autos and Trucks, the average speeds and speed variances at the first and the second pairs of speed limit signs were equal. The mean speeds for Autos were 12 to 13 mph and for Trucks 7 to 8 mph higher than the speed limit at the speed limit sign locations. The speed frequency and cumulative frequency distributions at different Influence Points are shown in Figure D.1 to D.26 (the Figures are at the end of this section).

Using the analysis of variance (ANOVA) method the speeds at different pairs of Influence Points were compared. The summary of the results of ANOVA method are shown in Table D.1. The results indicate whether the average speed at a given influence point is similar or different than the speed at another influence point. All Influence Points with the same grouping letter have the same speed level. For example, the Influence Point a has a grouping letter of A and no other influence point has this grouping letter in the Auto column. This indicates that the speed at Influence Point a is different than the speeds at other Influence Points. Similarly, at Influence Point b the grouping letters are B and C, indicating that the average speed at this point is similar to the average speed at any influence point which has grouping letter of B or C.

Speed Characteristics for Autos

The mean speed for Autos reduced from 63 mph at the beginning of taper (IP a) to 57 mph at 1200 ft before the bridge (IP g). It continued decreasing to 50 mph at the bridge (IP i). Then the speed increased to 56 mph at 1000 ft after the bridge (IP k), and kept increasing slightly until the end of study section (IP m). The speed of Autos over the bridge was as low as 24 and as high as 67 mph. At 500 feet after the bridge, the Autos' speed range was from 30 to 68 mph.

For Autos the standard deviations were around 7 mph on all locations, except over the bridge where it was 9.48 mph and 500 feet after the bridge, where the standard deviation is 8.35 mph. The large standard deviations indicate that the speed range was high on all Influence Points and even higher over the bridge.

Speed Characteristics of Autos on Taper

The speed distribution for IP a shows one peak around 66 mph and another one around 50 mph (see Figure D.1 and D.2). These two modal speeds indicate that there were two general groups of drivers. A small group of drivers were traveling around 50 mph,
Table D.1 Summary of ANOVA results for all Influence Points

<table>
<thead>
<tr>
<th>IPs</th>
<th>Waller Grouping</th>
<th></th>
<th>Duncan Grouping</th>
<th></th>
</tr>
</thead>
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<td></td>
<td>trucks</td>
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</tr>
<tr>
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<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
</tr>
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<td>b</td>
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<td>B, C, D</td>
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<td>J</td>
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<td>F</td>
<td>H, G</td>
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<td>l</td>
<td>D</td>
<td>F, E, G</td>
<td>D, E</td>
<td>E, F</td>
</tr>
<tr>
<td>m</td>
<td>D</td>
<td>E, D</td>
<td>D, E</td>
<td>E, C, D</td>
</tr>
</tbody>
</table>

but the rest of the drivers had a speed in the upper sixties or lower seventies. This distinct pattern became less obvious at the other locations as the vehicles traveled in the work zone. At IP a, all Autos traveled faster than 45 mph.

By the time the Autos reached the end of the taper (IP b), the average, maximum, and minimum speeds were decreased, but still almost all of the vehicles exceeded the speed limit. There are still two distinct groups of drivers, particularly a very high concentration at 62 mph, as shown in Figure D.3 and D.4. Comparison of speed distributions at IPs a and b indicates a shift in speed distribution toward the lower speeds.

*Speed Characteristics of Autos Near 1st Speed Limit Signs*

As the vehicles arrived at IP c, 500 ft before the first construction speed limit signs, a small decrease (1 mph) on the average speed was observed (see Table 3.1). However, still 98% of Autos drove faster than 45 mph. The speed distribution for this point (Figure D.5 and D.6) shows two peaks indicating that drivers were still traveling in two speed groups.
At the first construction zone speed limit signs (IP d), the average speed was 58 mph and 97% exceeded the speed limit (see Figure D.7 and D.8). The speed distributions at this point look very different than those of IP a. A gradual slope increase in the cumulative distribution curve indicates the drivers did not use a modal speed, but traveled at a wide range of speed around the mean.

After passing the first speed limit signs, the vehicles continued decreasing their speeds. This reduction can be seen by comparing the average speed and speed distributions at IP e (Figure D.9 and D.10) to those IPs c or d. Speed distributions for IP e show the shift from the higher speeds to the lower speeds. Even at Influence Point e, 93% exceeded the speed limit.

**Speed Characteristics of Autos at Uphill Section**

There is an uphill section from IP c (500 ft before the first speed limit signs) to IP f (top of upgrade section), see the study section profile Figure C.1. The influence point f is approximately at the Intersection Point of the vertical curve. The grade composition in this uphill section is shown in Table C.1.

Speed reduction adjustment data was collected on the uphill section to determine the effects of the uphill section on the speed of vehicles. The adjustment data were collected after the construction work was completed and traffic control devices were removed. The speeds were measured near (or at) IP c and IP f. The speed difference between these two points was determined for each vehicle. On the average, the speed of cars was not significantly affected by the uphill section. The mean speed reduction for cars was 1.00 mph. The speed change distribution for 116 cars was shown in Figure C.2.

The speed distribution at IP f has a mean of 56 mph, a standard deviation of 7 mph. The cumulative distribution curve for this point has one gentle slope (Figure D.11 and D.12). This gentle slope means the speeds are distributed evenly on the range. The standard deviation of 7 mph indicates that at this influence point, the shape of speed distribution has no significant difference from the others. There were 94% of the Auto drivers exceeding the 45 mph speed limit sign.

**Speed Characteristics of Autos Before Work Space**

There were two Influence Points before the work space, IP g (1200 feet before the bridge) and IP h (600 feet before the bridge or the work space). IP g, which is 1200 feet before the bridge, has the highest elevation in the study section. The average speed at this point increased by 1 mph, compared to that at IP f. This 1 mph speed increase might be due to the long distance between the
work space and this point. At this point, 95% of drivers exceeded the 45 mph speed limit (Figure D.13 and D.14).

At IP h, which is located 600 feet before the bridge, the mean speed was 52 mph and the standard deviation was 7.6 mph (see Figure D.15 and D.16). This mean speed is significantly different from the mean speed at IP g which was 57 mph. Within this 600 feet distance, a 5 mph speed reduction was obtained. Although the average speed was reduced, still 80% of Auto drivers exceeded the 45 mph speed limit, and 14% of Autos drivers traveled faster than 60 mph.

**Speed Characteristics of Autos At Work Space**

Over the bridge the average speed was the lowest (49.6 mph) and the speed distributions showed a significant shift toward the lower speeds (see Figure D.17 and D.18, IP i). However, still 65% of Autos drove faster than 45 mph. The range of speed was from 25 to 67 mph, with fewer drivers traveling near the upper bound of this range.

**Speed Characteristics of Autos After Passing Work Space**

After passing the bridge, the vehicles increased their speeds immediately and the speed distributions showed the shift toward higher speeds (see Figure D.19 and D.20). At IP j, 500 feet after the bridge, the average speed was increased to 52 mph. This speed is almost equal to the speed at IP h, (600 feet before the bridge). The analysis of variance of mean speeds indicated that the average speeds at these two influence points are not different. The standard deviation at IP j (8.3 mph) was less than that of the bridge, but greater than the others IP. The speed range here is as low as 30 mph, and as high as 68 mph. About 79% of Auto drivers exceeded the 45 mph speed limit and 19% drove faster than 60 mph.

At influence point k, 1000 feet after the bridge, drivers continued increasing their speeds (Figure D.21 and D.22). The average speed at IP k was 56 mph, a 4 mph increase over the speed IP j. At IP k, 98% of Auto drivers traveled faster than 45 mph, and 30% had speeds higher than 60 mph. Comparing the average speed at 1200 ft and 600 ft before the bridge, to those 500 ft and 1000 ft after the bridge it was found that the average speed profile was approximately symmetric around the bridge. The standard deviation of speed at IP k was 6.1 mph, which is the second smallest deviation (Table 3.1). This means that the speeds were relatively concentrated around the average speed. The smallest variance happened at IP 1 which is located 400 feet before the second speed limit sign.

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Speed Characteristics of Autos Near Second Speed Limit Signs

Influence Point 1 was 400 feet before the second speed limit signs. The smallest standard deviation was observed here; it was 5.9 mph. This indicates that the speeds at this point are more concentrated around the average speed, and the speed range is small (from 44 mph to 69 mph). The average speed here was 57 mph, which was 12 mph higher than the speed limit. About 97% of the drivers exceeded the 45 mph speed limit, and 30% of the drivers drove faster than 60 mph. The speed distribution and the cumulative frequency plots (Figure D.23 and D.24) show that the two modal speed appeared again.

At Influence Point m, which was the end of the study section, but not the end of the work zone, there was a second pair of construction speed limit signs. The signs at IP m were for drivers entering from the ramp as well as for the drivers going through. Comparing the speed distributions for points e and i with that of point m clearly shows the shift in speed.

It should be noted that, the average speed and speed distribution at the second speed limit signs (IP m) were very close to those at the first speed limit signs (IP d). The average speed at IP m increased to 57 mph, which is equal to the average speed at IP d. The shape and slope of the cumulative speed distribution curves for these points were very similar (Figure D.25 and D.26). Moreover, about the same number of drivers exceeded the speed limit at these two locations.

Speed Characteristics for Trucks

Similar to Autos, the maximum, minimum, and average speeds, and their standard deviations for Trucks are summarized in Table 3.1. The average speed for Trucks reduced from 57 mph at the beginning of taper (IP a) to 45.5 mph at the bridge (IP i), and then increased to 52 mph at the end of study section (IP m). For Trucks, the speed frequency and cumulative frequency distributions at different influence points are given in Figures D.1 to D.26. As it can be seen from the Figures, Trucks had only one modal speed, contrary to the Autos which showed two modal speeds at the first few Influence Points.

The range of speeds for Trucks was narrower than the range for Autos, as reflected by the smaller standard deviation for Trucks (it varied between 4.75 and 5.86). Interestingly, the largest variation in speed did not occur over the bridge, but was at the end of taper and before the first speed limit signs. Over the bridge, the speed of Trucks was as low as 35 mph and as high as 60 mph.
The speed distribution for Trucks showed one modal speed, as shown in Figure D.1 and D.2. The modal speed is very close to the mean speed. Unlike the Autos, most of the Trucks traveled around the mean speed. At Influence Point a, 100% of the Trucks traveled faster than 45 mph. By the time the Trucks reached the end of the taper, the average speed decreased by 3 mph and the speed distributions were shifted toward lower speeds. However, still 96% of the Trucks exceeded the speed limit. At Influence Point b, nearly one quarter of the Trucks traveled at the mean speed at this location. Figures D.3 and D.4 clearly show the concentration of speed around the mean speed.

Speed Characteristics of Trucks Near 1st Speed Limit Signs

As the Trucks approached Influence Point c, a large speed range was kept by the Trucks. The speed standard deviation at this location was as large as that of point b. It means that some Truck drivers reduced their speeds while others maintained higher speeds. Figures D.5 and D.6 show the wide range of speed distributions at this point. About 94% of the Trucks traveled faster than 45 mph.

At the first work zone speed limit signs (Influence Point d), the average speed was 54 mph and 94% of Trucks exceeded the speed limit. The speed distributions at this point showed more concentration around the mean speed (see Figure D.7 and D.8). A sharp slope increase in the cumulative distribution curve indicates that most Truck drivers traveled at a speed close to the mean speed.

After passing the first speed limit signs, the average speed of the Trucks decreased to 51 mph. This reduction can be seen by comparing the average speed and speed distributions at point e to those of point c or d. The speed distributions for IP e (Figure D.9 and D.10) show the shift from higher speeds to lower speeds. Even at Influence Point e, 88% of the Trucks exceeded the speed limit.

Speed Characteristics of Trucks at Uphill Section

There is an uphill section from IP c (500 ft before the first speed limit signs) to IP f (top of upgrade section), as shown in the study section profile in Figure C.1. The grade composition in this uphill section is shown in Table C.1. Adjustment data were collected on the uphill section after the work zone signs were removed in order to determine how much the upgrade section affected the truck speeds.

Speed changes between the beginning and the end of the upgrade
Figure D.1
Speed distribution for autos & trucks at IP a, (beginning of taper)

Figure D.2
Cumulative distribution for autos & trucks at IP a, (beginning of taper)
Figure D.3
Speed distribution for autos & trucks at IP b, (end of taper)

Figure D.4
Cumulative distribution for autos & trucks at IP b, (end of taper)
Figure D.5
Speed distribution for autos & trucks at IP c, (500ft before 1st SL)

Figure D.6
Cumulative distribution for autos & trucks at IP c, (500ft before 1st SL)
Figure D.7
Speed distribution for autos & trucks at IP d, (at 1st SL)

Percent

0 10 20 30 40 50 60 70 80
Speed (mph)

- Autos - Trucks

Figure D.8
Cumulative distribution for autos & trucks at IP d, (at 1st SL)

Cumulative percentage

0 20 40 60 80 100
Speed (mph)

- Autos - Trucks
Figure D.9
Speed distribution for autos & trucks at IP e, (500ft after 1st SL)

Figure D.10
Cumulative distribution for autos & trucks at IP e, (500ft after 1st SL)
were collected for 104 trucks. The average speed reduction was 5 mph with a standard deviation of 2.529 mph (Table C.2). The speed reduction distribution is shown in Figure C.3. This indicates that the average speed reduction due to this uphill section is about 5 mph.

Influence Point f is the point of intersection of two slopes for the vertical curve. The mean speed at IP f was 50 mph with standard deviation of 5.2 mph. The average speed is slightly lower than IP e and IP g, due to the uphill grade. The cumulative distribution of this point has one gentle slope (Figure D.11 and D.12). This gentle slope means Trucks' speeds are distributed evenly on the range. The standard deviation of 5.2 mph indicates that at this Influence Point, the shape of the speed distribution is not significantly different from the others. There were 76% of Truck drivers exceeding the 45 mph speed limit sign.

Speed Characteristics of Trucks Before Work Space

There were two influence points before the work space, IP g (1200 feet before the bridge) and IP h (600 feet before the bridge or the work space). The speed characteristics at these two influence points are described as follows.

IP g has the highest elevation on the vertical curve. The average speed at this point had a 0.4 mph increase compared to IP f (Figures D.13 and D.14). This 0.4 mph speed increase might be due to a relatively long distance the vehicles had to travel before reaching the work space. At this point, 82% of drivers exceeded the 45 mph speed limitation.

The mean speed at IP h was 47 mph, which is significantly different from the speed at IP g. Within this 600 feet travel, a 3 mph speed reduction was obtained (Figures D.15 and D.16). About 63% of the Truck drivers still drove faster than 45 mph.

Speed Characteristics of Trucks at Work Space

Over the Rt. 16 bridge (IP i), the average speed for Trucks dropped to its lowest value, and the speed distributions showed a very significant shift toward the lower speeds (see Figures D.17 and D.18). The average speed at this point was 45.5 mph and nearly half of the Truck drivers traveled faster than the speed limit. About 80% of Truck drivers maintained a speed within 5 mph of the speed limit.

Speed Characteristics of Trucks After Passing Work Space

After passing the bridge, the vehicles increased their speeds and the speed distributions showed a shift toward higher speeds (see Figures D.19 and D.20). At 500 feet after the bridge (IP j) the average speed of Trucks increased to 47.9 mph. The analysis of
Figure D.11
Speed distribution for autos & trucks at IP f, (end of upgrade section)

Figure D.12
Cumulative distribution for autos & trucks at IP f, (end of upgrade section)
Figure D.13
Speed distribution for autos & trucks at IPg, (1200ft before bridge)

Figure D.14
Cumulative distribution for autos & trucks at IPg, (1200ft before bridge)
Figure D.15
Speed distribution for autos & trucks at IP h, (600ft before bridge)

Figure D.16
Cumulative distribution for autos & trucks at IP h, (600ft before bridge)
Figure D.17
Speed distribution for autos & trucks at IP i, (at bridge)

Figure D.18
Cumulative distribution for autos & trucks at IP i, (at bridge)
variance indicated the speed at IP j is equal to the speed at IP h (600 feet before the bridge). The speed range here is from as low as 37 mph to as high as 62 mph. About 61% of Truck drivers exceeded the 45 mph speed limit.

At Influence Point k (1000 feet after the bridge) drivers continued increasing their speeds. The average speed at IP k was 50.2 mph and 88% of Truck drivers traveled faster than 45 mph (Figures D.21 and D.22). The speeds at 1200 and 600 feet before the bridge were very close to the speeds at 500 feet and 1000 feet after the bridge. The standard deviation at IP k was 4.75 mph (Table 3.1), indicating that the drivers traveled close to the average speed.

Speed Characteristics of Trucks Near Second Speed Limit Signs

Influence Point 1 was 400 feet before the second speed limit signs. The second smallest standard deviation was observed here (4.76 mph). The average speed here is 50.7 mph, which is 5.7 mph higher than the speed limit (Figures D.23 and D.24). About 88% of the Truck drivers exceeded 45 mph.

Like Autos, the Trucks continued increasing their speeds. At the last Influence Point in the study section, IP m, the average speed increased to 52 mph, although (see Figures D.25 and D.26) there was the second pair of work zone speed limit signs. The percent of Trucks exceeding the speed limit increased to 96%. Comparing this Influence Point with IP d, (at the first speed limit signs), the speed distributions are pretty similar.
Figure D.19
Speed distribution for autos & trucks
at IP j, (500ft after bridge)

Figure D.20
Cumulative distribution for autos & trucks at IP j, (500ft after bridge)
Figure D.21
Speed distribution for autos & trucks at IP k, (1000ft after bridge)

Figure D.22
Cumulative distribution for autos & trucks at IP k, (1000ft after bridge)
Figure D.23
Speed distribution for autos & trucks at IP 1, (400ft before 2nd SL)

Figure D.24
Cumulative distribution for autos & trucks at IP 1, (400ft before 2nd SL)
Figure D.25
Speed distribution for autos & trucks at IP m, (at 2nd SL signs)

Figure D.26
Cumulative distribution for autos & trucks at IP m, (at 2nd SL signs)