EVALUATION OF WORK ZONE SPEED LIMIT SIGNS WITH STROBE LIGHTS

By

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

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The construction zone speed limit sign used in Illinois consists of a regulatory 45 mph speed limit sign augmented with two small strobe lights and two orange colored plates. When the lights are flashing the speed limit is 45 mph. This report contains the findings from evaluation of the effectiveness of the flashing lights in reducing speeds in a rural interstate construction zone. The speed reduction effects on cars and trucks were determined at two locations within the work zone. The results indicated that the average speed of cars was reduced by 1.9-7.1 mph and that of trucks by 1.3-6.0 mph when the strobe lights were flashing. In general, the speed reduction effects were more pronounced on the cars than on the trucks, and at a location past the work space than before it. The reductions at the location past the work space were 2-3 times more than the reductions at the location before the work space. Cars reduced their speeds, on the average, by 1.9 to 4.9 mph before and by 5.9 to 7.1 mph after the work space. Similarly, the speed reduction for trucks was 1.3-2.9 mph before and 3.3-6.0 after the work space. In general, the percentages of vehicles with excessive speeds in the work zone decreased when the lights were flashing.
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The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy presented herein. The contents do not necessarily reflect the official views or policies of the Illinois Department of Transportation or the Federal Highway Administration.
# TABLE OF CONTENTS

ABSTRACT .................................................. ii

ACKNOWLEDGMENT AND DISCLAIMER ......................... iii

1. INTRODUCTION ........................................... 1
   1.1. Experiences with Flashing Beacons ................. 1

2. STUDY APPROACH ......................................... 3
   2.1. Site Description ................................... 3
   2.2. Data Collection ..................................... 3
   2.3. Data Reduction ..................................... 6
   2.4. Data Analysis ....................................... 7
       2.4.1. Speed Characteristics Analysis ............... 7
       2.4.2. Speed Reduction Analysis ...................... 8

3. ANALYSIS OF DATA SET 1 ................................ 9
   3.1. Speed Characteristics in Control Data Set 1 ..... 9
   3.2. Speed Characteristics in Treatment Data Set 1 ... 9
   3.3. Discussion of Speed Statistics for Data Set 1 ... 14
   3.4. The Effectiveness of Strobe Lights for Data Set 1 15
       3.4.1. Effectiveness of Strobe Lights on Cars .... 18
       3.4.2. Effectiveness of Strobe Lights on Trucks ... 18
   3.5. Conclusions for Data Set 1 ......................... 18

4. ANALYSIS OF DATA SET 2 ................................ 20
   4.1. Speed Characteristics in Control Data Set 2 ..... 20
   4.2. Speed Characteristics in Treatment Data Set 2 ... 20
   4.3. Discussion of Speed Statistics for Data Set 2 ... 25
   4.4. Effectiveness of Strobe Lights for Data Set 2 ... 26
       4.4.1. Effectiveness of Strobe Lights on Cars ... 29
       4.4.2. Effectiveness of Strobe Lights on Trucks ... 29
   4.5. Conclusions for Data Set 2 ......................... 29

5. ANALYSIS OF DATA SET 3 ................................ 31
   5.1. Speed Characteristics in Control Data Set 3 ..... 31
   5.2. Speed Characteristics in Treatment Data Set 3 ... 31
   5.3. Discussion of Speed Statistics for Data Set 3 ... 36
   5.4. Effectiveness of Strobe Lights for Data Set 3 ... 37
       5.4.1. Effectiveness of Strobe Lights on Cars ... 40
       5.4.2. Effectiveness of Strobe Lights on Trucks ... 40
   5.5. Conclusions for Data Set 3 ......................... 40
1. INTRODUCTION

Regulatory 45 mph speed limit signs are placed in Illinois' rural interstate construction zones. The construction zone speed limit sign used in Illinois consists of a regulatory 45 mph speed limit sign with two small strobe lights and two orange colored plates added to it. The wording on the orange plates indicates that when the lights are flashing the speed limit is 45 mph. The flashing light are turned off when the crew is not working.

This report contains the findings from evaluation of the effectiveness of the flashing lights in reducing speeds in a rural interstate construction zone. The speed reduction effects on cars and trucks were determined at two locations within the work zone. Three different data sets were used for this analysis. The results for each data set will be discussed separately.

Only free flow vehicles were used for data analysis to eliminate the effects of platooning. It was assumed that a vehicle was traveling at free flow traffic, when its headway was greater than 5 seconds. When the headway was less than or equal to 5 seconds, the vehicle was considered to be traveling in a platoon; therefore, its speed was influenced by the speed of the leading vehicle.

1.1. Experiences with Flashing Beacons

Flashing beacons are often used at locations on highways to call the attention of drivers to a specific message on a sign. The Illinois construction speed limit signs have two strobe lights mounted on top of regulatory speed limit signs to call attention of the drivers to the speed limit. The strobe lights are a lot smaller than the flashing beacons used, say, in school zones. This study will determine the speed reduction effects of the speed limit signs augmented with the strobe lights. Graham (1) studied the effects of active warning of speed zoning in a rural freeway construction zone where the roadway was reduced to a two-lane, two-way operation by means of a crossover section. The active warning of speed zoning consisted of high intensity flashing lights mounted on the regulatory or advisory speed zone signs. The active warning of speed zoning did not effect speeds, but did reduce the erratic maneuver rate significantly (1).

Lyles (2) conducted an experiment in which two 8" flashing beacons were added to each of the MUTCD (3) signs in a work zone in which one lane of a two-lane rural highway was closed. The short lane closure was staged to resemble a maintenance zone with one lane open during the day and two lanes open at night (there were no workers or flaggers present). When the signs were augmented with the flashing beacons, they were 47-119% more effective in reducing the speed of vehicles than when they were not (base condition) (2). It was suggested that signs augmented with flashing beacons should be considered as an effective device for advance warning (2).
Goldblatt (4) developed a set of guidelines for installation of vehicle activated flashing beacons for speed and speed limit control on curves. Koziol et al. (5) evaluated effects of hazard identification lights and speed violation signs in rural school zones and small communities. Flashing beacons were effective in reducing traffic speeds when used at intersections or on curves (4), and in school zones or on approaches to small communities (5). Flashing beacons increased drivers' awareness of roadside conditions (5).
2. STUDY APPROACH

The study approach used for this project is commonly known as a before and after study with control groups. The existing work zone condition is considered to be the control group (strobe lights were turned off). When the two strobe lights were turned on it was considered a treatment condition. Data were collected for treatment and control conditions for six different time periods. This yielded 3 independent data sets for the same work zone. Each set is analyzed separately to check the validity of the findings from another data sets. Brief descriptions of the data collection site and these experiments are given below.

2.1. Site Description

The work zone was located on I-57 near Mattoon, Illinois, and was about 4 miles long. The construction crew were mainly working on two bridges (bridge deck repair). Other work zone activities involved shoulder improvements and other minor repair work. The Illinois standard traffic control plan for one lane closure on a rural highway was used in this location. The layout of the construction zone and the signs used are schematically shown in Figure 2.1. The highway had two lanes per direction with one lane closed and the other lane open to traffic. The average daily traffic on this section of I-57 is 11,800 vehicles.

2.2. Data Collection

The data were collected for 3 days which are defined as Data Sets 1 through 3. Each data set has two time periods. In one time period the strobe lights were turned on, and in the other time period the lights were turned off. The data collection schedule is shown in Table 2.1.

Table 2.1. The Data collection Schedule for Data Sets

<table>
<thead>
<tr>
<th>Data Set</th>
<th>Strobe Lights</th>
<th>Time</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ON</td>
<td>3:00-4:00 PM.</td>
<td>6/4/90</td>
</tr>
<tr>
<td></td>
<td>OFF</td>
<td>4:00-5:30 PM.</td>
<td>6/4/90</td>
</tr>
<tr>
<td>2</td>
<td>ON</td>
<td>3:40-5:10 PM.</td>
<td>6/5/90</td>
</tr>
<tr>
<td></td>
<td>OFF</td>
<td>5:10-6:10 PM.</td>
<td>6/5/90</td>
</tr>
<tr>
<td>3</td>
<td>ON</td>
<td>9:40-12:00 Noon</td>
<td>6/12/90</td>
</tr>
<tr>
<td></td>
<td>OFF</td>
<td>4:00-5:40 PM.</td>
<td>6/12/90</td>
</tr>
</tbody>
</table>
Figure 2.1 Work Zone Signs on SB I-57 During Strobe Lights Study

Indicates arrow board
Figure 2.2 Locations of Speed Stations on SB I-57 for Data Sets 1 thru 3 in Strobe Lights Study
There were three data collection stations: Station 1, 2 and 3. The data collection set up is shown in Figure 2.2. The vehicle speeds at each station were collected using mechanical traffic counters. The traffic counters were the IRD Traffic Counter and Classifiers (TCC) type. The counters were programmed to keep a record of individual vehicles. This was ascertained to be more accurate than having the traffic counter sort the data and store them in bins.

The strobe lights were mounted on top of regulatory 45 mph speed limit signs. The regulatory signs were located about 1500 ft past the beginning of the lane closure taper. The regulatory sign also had orange plates attached to the top and bottom of the sign to indicate when the sign was in effect.

The time periods were selected such that there would be no other factors (e.g. a police presence at work zone) that could influence the drivers' behavior. Graduate research assistants were monitoring the data collection stations to record any activities in the vicinity of the stations. At all three stations, mechanical traffic counters and road tubes were used for data collection.

Station 1, was located on a section of the highway that had been cold milled a few years before and was not resurfaced. The cold milled section was about 20 miles long and ended before the work zone. On the milled section, the pavement surface was not very smooth and the tires made more noise than on a regular pavement. The rough surface and the noise may have been the reasons for relatively lower speeds at Station 1 compared to the data from a work zone on the northbound of the same highway.

2.3. Data Reduction

The raw traffic data collected by the TCCs were stored in the internal memory of the unit. Each TCC can store individual records of up to 8,000 vehicles. The data were downloaded to an IBM PC and were stored in an ASCII format. In order to reduce the traffic data to meaningful results, a Fortran program called TRAFFIC was written to perform sorting, classification, and error checking on the raw data. The TRAFFIC program deletes any duplicated entries from the file, separates the data according to lane traveled, computes the headway for successive vehicles in each lane, filters out erroneous data, and separates free flow traffic data from that of platooning vehicles.

A vehicle is considered to be in free flow condition when its headway was greater than 5 seconds. When the headway was less than or equal to 5 seconds, it was assumed that the vehicle was traveling in a platoon, and therefore was influenced by the leading vehicle. Only free flow vehicles were considered in this study. For more information on data reduction refer to Appendix A.
2.4. Data Analysis

All statistical analyses were performed using the personal computer (PC) version of Statistical Analysis System (SAS) software, PC-SAS Version 6.04 (6). A separate statistical analysis was performed for cars and trucks.

Two types of analyses were conducted: (1) Speed characteristics analysis, and (2) Speed reduction analysis. For the speed characteristics analysis, speed distribution and speeding problems were examined. For the speed reduction analysis, the net changes in speeds when the lights were flashing compared to the control conditions were studied.

2.4.1. Speed Characteristics Analysis

The minimum, mean, and maximum speeds, standard deviation, frequency distribution, and percentage of vehicles exceeding a given speed level were determined. F-tests and t-tests were performed to compare speed variances and mean speeds, respectively. The two tests are briefly discussed below. A 95% confidence level is used when it is not stated otherwise.

For testing the hypothesis that, for example, the speed variance for cars was equal to that of trucks, an F-test was used. The calculated F-value is expressed as:

\[
F = \frac{S^2_{cr}}{S^2_{tr}}
\]

Where:

- \( S^2_{cr} \) = Speed variance of cars.
- \( S^2_{tr} \) = Speed variance of trucks.

For testing the hypothesis that, for example, the mean speed of cars was equal to the mean speed of trucks, a t-test was used. The t-value is computed from the following equation:

\[
t = \frac{\bar{U}_{cr} - \bar{U}_{tr}}{S_d}
\]

where:

- \( \bar{U}_{cr} \) = The mean speed of cars,
- \( \bar{U}_{tr} \) = The mean speed of trucks, and
- \( S_d \) = The standard deviation of the difference between mean speed of cars and trucks.
One assumption that was needed in order to use the t-test was that the speed data had a normal distribution. The data used in this study were for free flow vehicles and therefore did not necessarily have a normal distribution. However, the t-test was still viable because of its relative insensitivity to normal distributions (7). When the distributions of speeds were not the same (unequal variances), an approximate value of 't' was used to reflect the difference in the shape of the distributions (6).

2.4.2. Speed Reduction Analysis

In order to find out whether there were additional speed reductions due to turning strobe lights on in the construction zone, the net speed reductions were computed. The net speed reduction at Station 2 was computed using the data from Station 1 as the control station. In other words, the speed difference between the treatment and control data at Station 1 was used as the expected value for the speed difference at Station 2, if lights were not flashing.

A t-test with 95% confidence level was used to determine if the net reduction was statistically significant. The t-test was made by determining the net speed change from the following equation:

\[
\text{Net speed change at Station } n = (\bar{U}_{nt} - \bar{U}_{nc}) - (\bar{U}_{1t} - \bar{U}_{1c})
\]

Where:

- \(\bar{U}_{1t}\) = The treatment mean speed at Station 1.
- \(\bar{U}_{nt}\) = The treatment mean speed at Station n, n=2 or 3.
- \(\bar{U}_{1c}\) = The mean speed for control data at Station 1.
- \(\bar{U}_{nc}\) = The mean speed for control data at Station n, n=2 or 3.
3. ANALYSIS OF DATA SET 1

The data analysis consists of describing speed statistics for
the vehicles when the strobe lights were off and on, and finding
the net speed reduction to see whether or not there were additional
speed reductions when the strobe lights were turned on. For the
speed characteristics study, the minimum, maximum, and average
speed, speed variance, and percentage of traffic exceeding a given
speed level were determined for cars and trucks. A summary of
speed statistics for Data Set 1 is presented in Table 3.1. The
speed frequency distributions are shown in Figures 3.1 through 3.6.
The effects of strobe lights on cars and trucks are analyzed
separately, because the speed limit was 65 mph for cars and 55 for
trucks outside the work zone. Station 1 was outside of the traffic
control zone, but Stations 2 and 3 were inside where the speed
limit is 45 mph for all vehicles.

3.1. Speed Characteristics in Control Data Set 1

At least 83% of vehicles at Station 1, 96% at Station 2, and
100% at Station 3 exceeded the speed limits (see Table 3.1). Cars
and trucks reduced their speeds at Station 2, but increased them
after passing the work space. The average speeds of cars and
trucks at Station 3 were 13 and 15 mph, respectively, higher than
their average speeds at Station 2. The speeds at Station 3 were
even slightly higher than the speeds at Station 1.
The average speeds of cars and trucks were statistically
different at all three stations. Cars traveled 2-4 mph faster than
trucks. The speed frequency distributions for control data are
shown in Figures 3.1 through 3.3.
The speed distributions at Station 3 were more dispersed than
at the other two stations. The speed variances of cars and trucks
were statistically equal at Stations 1 and 2, but not at Station 3.
At Station 3 trucks had a higher standard deviation than the cars.
The results of comparisons of speed of cars to trucks are shown in
Table 3.2.

3.2. Speed Characteristics in Treatment Data Set 1

Similar to the control data, over 77% of vehicle at Station 1,
90% at Station 2, and 98% at Station 3 exceeded the speed limits
(see Table 3.1). Vehicles reduced their speeds at Station 2 and
increased them at Station 3. Cars and trucks increased their
speeds by 10 and 13 mph, respectively, between Stations 2 and 3.
For cars, the average speed at Station 3 was lower than the speed
at Station 1, but for trucks they were at the same level.
Cars traveled faster than trucks at Stations 1 and 2, but at
Station 3 they had similar speeds (see Table 3.2). The speed
frequency distributions are shown in Figures 3.4 through 3.6. The
<table>
<thead>
<tr>
<th></th>
<th>Control Data (Strobe Lights Off)</th>
<th>Treatment (Strobe Lights On)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Station 1</td>
<td>Station 2</td>
</tr>
<tr>
<td>No. of Veh</td>
<td>238</td>
<td>84</td>
</tr>
<tr>
<td>Mean Speed</td>
<td>69.95</td>
<td>58.34</td>
</tr>
<tr>
<td>Min Speed</td>
<td>46</td>
<td>55</td>
</tr>
<tr>
<td>Max Speed</td>
<td>89</td>
<td>78</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>5.43</td>
<td>4.23</td>
</tr>
<tr>
<td>Percent Exceeding Speed Limit</td>
<td>83.2%</td>
<td>98.9%</td>
</tr>
</tbody>
</table>

* Indicates percent exceeding 45 mph.
** Indicates percent exceeding 55 mph.
*** Indicates percent exceeding 65 mph.
Figure 3.1. Speed Frequency at Station 1
For Data Set 1 When Lights Were Off

Percent of Observations

![Bar graph showing speed frequency at Station 1.]

Figure 3.2. Speed Frequency at Station 2
For Data Set 1 When Lights Were Off

Percent of Observations

![Bar graph showing speed frequency at Station 2.]
Figure 3.3. Speed Frequency at Station 3  
For Data Set 1 When Lights Were Off

Figure 3.4. Speed Frequency at Station 1  
For Data Set 1 When Lights Were On
Figure 3.5. Speed Frequency at Station 2
For Data Set 1 When Lights Were On

Figure 3.6. Speed Frequency at Station 3
For Data Set 1 When Lights Were On
speed variances of cars and trucks were statistically equal at all three stations. The speed distributions at Station 3 did not appear to be bell-shaped, indicating that vehicles did not follow a modal speed. The wide dispersion is also reflected by higher speed variances of 7.63 and 6.82 mph for cars and trucks, respectively.

Table 3.2.
Comparison of Mean Speed and Speed Variance of Cars and Trucks for Data Set 1

<table>
<thead>
<tr>
<th>Condition</th>
<th>Station</th>
<th>Speed Variances</th>
<th>Mean Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Prob&gt;F'</td>
<td>Inference</td>
</tr>
<tr>
<td>Control</td>
<td>1</td>
<td>0.0088</td>
<td>unequal</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.0022</td>
<td>unequal</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.5089</td>
<td>equal</td>
</tr>
<tr>
<td>Treatment</td>
<td>1</td>
<td>0.4908</td>
<td>equal</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.3577</td>
<td>equal</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.4811</td>
<td>equal</td>
</tr>
</tbody>
</table>

3.3. Discussion of Speed Statistics for Data Set 1

Vehicles reduced their speeds at Station 2, but increased them at Station 3. Cars and trucks traveled 13 and 15 mph, respectively, faster at Station 3 than at Station 2 when the lights were not flashing. However, when the lights were flashing, the speed differences between Stations 2 and 3 were reduced to 10 mph for cars and 13 mph for trucks. The average speeds of cars and trucks inside the work zone were lower when the lights were flashing compared to when they were off (see Figure 3.7).

Within the work zone as well as outside of it, cars and trucks exceeded the speed limits. Although trucks traveled about 4 mph slower than cars at Station 1, a higher percentage of trucks exceeded the speed limit at Station 1. About 16-18% more trucks than cars exceeded the speed limit at Station 1. It should be noted that the speed limit for trucks was also 10 mph less than that of cars.

Inside the work zone, cars traveled faster than trucks, except at Station 3 when the lights were flashing. At Station 3, the average speeds of cars and trucks were equal when the strobe lights were on. The speed limit in the work activity area was 45 mph for
both types of vehicles. At Station 3, 100% of cars and trucks were traveling faster than the speed limit.

Over 90% of drivers, except the car drivers at Station 1, were traveling faster than speed limits for both control and treatment conditions. The percentages of vehicles exceeding a speed level are shown in Figures 3.8 through 3.11. As the figures show, there were fewer vehicles with very high speeds at Station 2 compared to Station 3. Also, the percentage of vehicles with excessive speeds decreased when the lights were flashing in comparison to the control data.

3.4. Effectiveness of Strobe Lights for Data Set 1

In order to find out whether there was an additional speed reduction when the lights were flashing, the net speed reduction was computed using the procedure described in the Study Approach section. The net reductions are summarized in Table 3.3.
Figure 3.8. Cars Exceeding Given Speed
For Data Set 1 When Lights Were off

Figure 3.9. Cars Exceeding Given Speed
For Data Set 1 When Lights Were On
Figure 3.10. Trucks Exceeding Given Speed
For Data Set 1 When Lights Were Off

Figure 3.11. Trucks Exceeding Given Speed
For Data Set 1 When Lights Were On
Table 3.3
Net Speed Reductions (mph) For Data Set 1

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>Between Station 1 and 2</th>
<th>Between Station 1 and 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Net Speed Reduction</td>
<td>T-test Inference</td>
</tr>
<tr>
<td>Cars</td>
<td>3.66</td>
<td>significant</td>
</tr>
<tr>
<td>Trucks</td>
<td>1.27</td>
<td>not significant</td>
</tr>
</tbody>
</table>

3.4.1. Effectiveness of Strobe Lights on Cars

The net speed reduction for cars at Station 2 was 3.66 mph. The result of a t-test indicated that the net reduction is statistically significant. This indicates that the strobe lights additionally reduced the average speed of cars by 3.66 mph. The net speed reduction for cars at Station 3 was 5.86 mph, and it was also statistically significant. This means that when the lights were flashing the average speed of cars was reduced by 5.86 mph. Therefore, using the strobe lights was effective in reducing speed of cars at Stations 2 and 3.

3.4.2. Effectiveness of Strobe Lights on Trucks

The net speed reduction for trucks at Station 2 was equal to 1.27 mph. The result of t-test shows that this difference is not statistically significant. On the other hand, the net speed reduction for truck at Station 3 was equal to 3.29 mph, and this difference was statistically significant. Thus, the flashing lights did not significantly reduced the average speed of trucks at Station 2, but did at Station 3.

3.5. Conclusions for Data Set 1

The results from Data Set 1 indicate that when the lights on the speed limit signs were flashing, the average speed of cars was reduced by 3.7-5.9 mph, and the average speed of trucks by 1.3-3.3 mph inside the work zone. The lights on the speed limit signs did not significantly reduce the average speed of trucks near the beginning of the one lane section, but did reduce it further down the line in the work zone. Thus, when the lights were flashing the cars traveled about 3.7 mph slower before reaching the work space, and 5.9 mph slower after passing the work space. However, trucks only traveled 3.3 mph slower after passing the work space. In
general, the percentages of vehicles with excessive speeds in the work zone decreased when the lights were flashing.
4. ANALYSIS OF DATA SET 2

The analysis of Data Set 2 is very similar to that of Data Set 1. Descriptions of speed statistics when the strobe lights were on and off are provided, and the net speed reductions are computed to assess whether or not there were additional speed reductions when the lights were flashing. A summary of speed characteristics for Data Set 2 are presented in Table 4.1, and speed frequency distributions are shown in Figures 4.1 through 4.6. In the following sections the speed characteristics for cars and trucks for Data Set 2 are discussed in detail.

Data Set 2 contains a higher percentage of trucks that Data Set 1. According to the information from IDOT's ADT Maps, the percentage of commercial vehicles at this location is about 22%. However, the percentage of trucks in Data Set 2 is higher than this value. The highest percentage of trucks is 47% at Station 3 for the treatment condition. The reason for the higher percentage of trucks is because only free flow vehicles were considered and Data Set 2 contained more trucks in free flow condition.

4.1. Speed Characteristics in Control Data Set 2

Similar to Data Set 1, cars and trucks reduced their speeds at Station 2, but increased them after passing the work space. At least 75% of vehicles at Station 1, 88% at Station 2, and 100% at Station 3 exceeded the speed limits (see Table 4.1). The average speeds of cars and trucks at Station 3 were 16 and 17 mph, respectively, higher than their average speeds at Station 2.

The average speeds of cars and trucks were statistically different at all three stations. Cars traveled 3-6 mph faster than trucks. Speed frequency distributions for control data are shown in Figures 4.1 through 4.3.

The speed distribution of trucks was shifted to the left of cars at Station 1. The speed variances of trucks at Station 2 were significantly lower than those of cars. However, the speed variances of cars and trucks were statistically equivalent at Stations 1 and 3. The results of comparisons of speeds of cars to speeds of trucks are summarized in Table 4.2.

4.2. Speed Characteristics in Treatment Data Set 2

The vehicles reduced their speeds at Station 2 and increased them at Station 3. Cars and trucks traveled 11 and 13 mph, respectively, faster at Station 3 than Station 2. The speeds at Station 3 were slightly lower than the speeds at Station 1. Over 76% of vehicles at Station 1, 79% at Station 2, and 100% at Station 3 exceeded the speed limits (see Table 4.1).

The average speeds of cars and trucks were statistically different at all three stations (see Table 4.2). Cars traveled
Table 4.1 Summary of Speed Statistics for Data Set 2

<table>
<thead>
<tr>
<th></th>
<th>Control Data (Strobe Lights Off)</th>
<th>Treatment (Strobe Lights On)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Station 1</td>
<td>Station 2</td>
</tr>
<tr>
<td></td>
<td>Cars</td>
<td>Trucks</td>
</tr>
<tr>
<td>No. of Veh</td>
<td>146</td>
<td>51</td>
</tr>
<tr>
<td>Mean Speed</td>
<td>68.03</td>
<td>62.82</td>
</tr>
<tr>
<td>Min Speed</td>
<td>48</td>
<td>53</td>
</tr>
<tr>
<td>Max Speed</td>
<td>80</td>
<td>74</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>5.12</td>
<td>4.58</td>
</tr>
<tr>
<td>Percent Exceeding Speed Limit</td>
<td>74.7</td>
<td>**</td>
</tr>
</tbody>
</table>

* Indicates percent exceeding 45 mph.
** Indicates percent exceeding 55 mph.
*** Indicates percent exceeding 65 mph.
Figure 4.1. Speed Frequency at Station 1
For Data Set 2 When Lights Were Off

Figure 4.2. Speed Frequency at Station 2
For Data Set 2 When Lights Were Off
Figure 4.3. Speed Frequency at Station 3
For Data Set 2 When Lights Were Off

![Bar chart showing speed frequency at station 3 with data for cars and trucks when lights were off.]

Figure 4.4. Speed Frequency at Station 1
For Data Set 2 When Lights Were On

![Bar chart showing speed frequency at station 1 with data for cars and trucks when lights were on.]

23
faster than trucks at all three stations. The speed frequency
distributions are shown in Figures 4.4 through 4.6.

The speed variance of cars at Station 2 was higher than that
of trucks. However, the variances of cars and trucks were
statistically equivalent at Stations 1 and 3. The speed frequency
curves are not bell-shaped at Station 3, but they are bell-shaped
at the rest of the stations. This means that vehicles did not
follow a modal speed at Station 3. The wide speed dispersion at
Station 3 is also reflected by higher speed variances of 8.29 and
6.85 mph for cars and trucks, respectively.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Station</th>
<th>Speed Variances</th>
<th>Mean Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Prob&gt;</td>
<td>F'</td>
</tr>
<tr>
<td>Control</td>
<td>1</td>
<td>0.3674</td>
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</tr>
<tr>
<td></td>
<td>2</td>
<td>0.0164</td>
<td>unequal</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.0643</td>
<td>equal</td>
</tr>
<tr>
<td>Treatment</td>
<td>1</td>
<td>0.1925</td>
<td>equal</td>
</tr>
<tr>
<td></td>
<td>2</td>
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<td>unequal</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.0807</td>
<td>equal</td>
</tr>
</tbody>
</table>

4.3. Discussion of Speed Statistics for Data Set 2

Similar to Data Set 1, vehicles reduced their speeds at
Station 2, but increased them at Station 3. When the lights were
not flashing, cars and trucks traveled 16 and 17 mph, respectively,
faster at Station 3 than Station 2. However, when the lights were
flashing, the speed differences between Stations 2 and 3 were
reduced to 11 mph for cars and 13 mph for trucks. As shown in
Figure 4.7, the average speeds of cars and trucks inside the work
zone were lower when the lights were flashing compared to when they
were off.

Cars and trucks exceeded the speed limits both inside and
outside of the work zone. Although trucks traveled slower than
cars at Station 1, the percentage of trucks exceeding the speed
limit at Station 1 was 20-23% higher than that of cars. It should be noted that the speed limit for trucks was also 10 mph less than that of cars. On the other hand, cars traveled faster than trucks inside the work zone, although the speed limit was the same for both types of vehicles. At Station 3, 100% of cars and trucks were traveling faster than the speed limit.

Inside the work zone, the percentage of vehicles with excessive speeds decreased when the lights were flashing compared to the control data. The percentages of vehicles exceeding a speed level are shown in Figures 4.8 through 4.11. As the figures show, there were also overall decreases in the number of vehicles with very high speeds at Station 2 compared to Station 3 when the lights were flashing.

4.4. Effectiveness of Strobe Lights for Data Set 2

To find out whether there was an additional speed reduction when the lights were flashing, the net speed reductions for cars and trucks at Stations 2 and 3 were computed using the procedure described in the Study Approach section. The net reductions are summarized in Table 4.3.
Figure 4.8. Cars Exceeding Given Speed For Data Set 2 When Lights Were Off

Figure 4.9. Cars Exceeding Given Speed For Data Set 2 When Lights Were On
Figure 4.10. Trucks Exceeding Given Speed
For Data Set 2 When Lights Were Off

Figure 4.11. Trucks Exceeding Given Speed
For Data Set 2 When Lights Were On
Table 4.3
Net Speed Reductions (mph) For Data Set 2

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>Between Station 1 and 2</th>
<th>Between Station 1 and 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Net Speed Reduction</td>
<td>T-test Inference</td>
</tr>
<tr>
<td>Cars</td>
<td>1.92</td>
<td>significant</td>
</tr>
<tr>
<td>Trucks</td>
<td>1.81</td>
<td>significant</td>
</tr>
</tbody>
</table>

4.4.1. Effectiveness of Strobe Lights on Cars

The net speed reduction for cars at Station 2 was 1.92 mph. The result of a t-test indicated that the net reduction is statistically significant. This indicates that the strobe lights additionally reduced the average speed of cars by 1.92 mph. The net speed reduction for cars at Station 3 was 7.01 mph, and it also was statistically significant. This means that when the lights were flashing the average speed of cars was additionally reduced by 7.01 mph at Station 3. Therefore, using the strobe lights was effective in reducing the speeds of cars at Stations 2 and 3.

4.4.2. Effectiveness of Strobe Lights on Trucks

The net speed reductions for trucks at Stations 2 and 3 were 1.81 and 5.81 mph, respectively. The result of t-tests show that those differences are statistically significant. Thus, the strobe lights additionally reduced the average speed of trucks by 1.81 mph at Station 2 and by 5.81 mph at Station 3. Thus, using the strobe lights was effective in reducing the speeds of trucks inside the work zone.

4.5. Conclusions for Data Set 2

The results from Data Set 2 indicated that when the lights on the speed limit signs were flashing, cars and trucks reduced their speeds. The strobe lights were effective in reducing the average speed of cars by 1.9-7.0 mph, and the average speed of trucks by 1.8-5.8 mph inside the work zone. The strobe lights on the speed limit sign not only reduced the average speed of vehicles near the beginning of the one lane section, but also reduced the speeds further down the line in the work zone. Thus, when the lights were flashing the vehicles traveled about 1.8-1.9 mph slower before
reaching the work space, and 5.8-7.0 mph slower after passing the
work space. Furthermore, when the lights were flashing, the
percentages of vehicles with excessive speeds inside the work zone
decreased.
The analysis of Data Set 3 is similar to Data sets 1 and 2. The speed statistics for the vehicles when the lights were on and off are discussed, and the findings on the effectiveness of the strobe lights on reducing speeds are presented. A summary of speed statistics for Data Set 3 are presented in Table 5.1, and the speed frequency distributions are shown in Figures 5.1 through 5.6. In the following sections, the speed characteristics for cars and trucks for Data Set 3 are discussed in detail.

5.1. Speed Characteristics in Control Data Set 3

As shown in Table 5.1, the vehicles traveled slower at Station 2 than at Stations 1 and 3. The mean speeds of vehicles at Station 2 were 10-11 mph lower than those at Station 1, and 8-10 mph lower than those at Station 3. Over 66% of cars and 94% of trucks exceeded the speed limits at Station 1. Similarly, at least 95% of vehicles at Station 2 and 100% at Station 3 traveled faster than the 45 mph speed limit.

The average speeds of cars were about 3-4 mph higher than those of trucks, and they were statistically different at all three stations (see Table 5.2). This difference in speed can easily be seen in the speed distributions plots shown in Figures 5.1 through 5.3. The speed variances for cars and trucks were equal at Stations 1 and 3. However, at Station 2, cars had a higher speed variance than trucks.

5.2. Speed Characteristics in Treatment Data Set 3

Similar to the Control data, cars and trucks significantly reduced their speeds at Station 2, but increased their speeds slightly after passing the work space. The mean speeds of vehicles at Station 2 were 13-15 mph lower than those at Station 1, and 6-7 mph lower than those at Station 3. Over 71% of cars at Station 1 and around 92% at Stations 2 and 3 exceeded the speed limits (see Table 5.1). The percentage of speeding trucks was 90% at Station 1, decreased to 75% at Station 2, and increased to 90% again at Station 3.

Cars traveled as much as 3 to 6 mph faster than trucks, and the results of t-tests showed that the mean speeds of cars are significantly higher than those of trucks at all three stations. The speed distribution plots in Figures 5.4 through 5.6 clearly show this shift. The speed variances of cars and trucks were statistically equal to each other at Station 1 and 3, but not at Station 2. The speed distributions at Station 3 did not appear to be bell-shaped, indicating that vehicles did not follow a modal speed. The wide dispersion is also reflected by higher speed variances of 8.40 and 7.66 mph for cars and trucks, respectively.
Table 5.1 Summary of Speed Statistics for Data Set 3

<table>
<thead>
<tr>
<th></th>
<th>Control Data (Strobe Lights Off)</th>
<th>Treatment (Strobe Lights On)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Station 1</td>
<td>Station 2</td>
</tr>
<tr>
<td></td>
<td>Cars</td>
<td>Trucks</td>
</tr>
<tr>
<td>No. of Veh</td>
<td>216</td>
<td>113</td>
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<tr>
<td>Mean Speed</td>
<td>67.62</td>
<td>63.54</td>
</tr>
<tr>
<td>Min Speed</td>
<td>47</td>
<td>49</td>
</tr>
<tr>
<td>Max Speed</td>
<td>90</td>
<td>85</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>5.68</td>
<td>5.22</td>
</tr>
<tr>
<td>Percent Exceeding</td>
<td>66.2</td>
<td>94.7</td>
</tr>
<tr>
<td>Speed Limit</td>
<td>***</td>
<td>**</td>
</tr>
</tbody>
</table>

* Indicate percent exceeding 45 mph.
** Indicates percent exceeding 55 mph.
*** Indicates percent exceeding 65 mph.
Figure 5.1. Speed Frequency at Station 1
For Data Set 3 When Lights Were Off

Figure 5.2 Speed Frequency at Station 2
For Data Set 3 When Lights Were Off
Figure 5.3. Speed Frequency at Station 3
For Data Set 3 When Lights Were Off

Figure 5.4. Speed Frequency at Station 1
For Data Set 3 When Lights Were On
Figure 5.5. Speed Frequency at Station 2
For Data Set 3 When Lights Were On

Figure 5.6. Speed Frequency at Station 3
For Data Set 3 When Lights Were On
Table 5.2
Comparison of Mean Speed and Speed Variance of Cars and Trucks for Data Set 3

<table>
<thead>
<tr>
<th>Condition</th>
<th>Station</th>
<th>Speed Variances</th>
<th>Mean Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Prob&gt;F’</td>
<td>Inference</td>
</tr>
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<td>Control</td>
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<td>0.3185</td>
<td>equal</td>
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<td>3</td>
<td>0.2842</td>
<td>equal</td>
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</tbody>
</table>

5.3. Discussion of Speed Statistics for Data Set 3

Cars and trucks reduced their speeds at Station 2, but increased them at Station 3. There were also overall decreases in the number of vehicles with very high speeds at Station 2 compared to Station 3. The speed increase between Stations 2 and 3 was around 8-10 mph when the lights were turned off, and 6-7 mph when the lights were flashing. Inside the work zone, cars traveled about 3-4 mph faster than trucks (see Figure 5.7). The average speeds of cars and trucks were much lower when the lights were flashing compared to when they were off.

The percentage of vehicles with excessive speeds was lower when the lights were flashing than when the lights were off, but a very large portion of cars and trucks still exceeded the speed limit. This trend can be seen in Figures 5.8 through 5.11. When the lights were off, the percentages of trucks exceeding the speed limit were 96% and 100% at Stations 2 and 3, respectively. However, when the lights were on, the percentages were reduced to 75% at Station 2 and 90% at Station 3. Similarly, the percentage of cars exceeding the speed limit decreased from 98-100% when the lights were off to 90-93% when the lights were flashing.

Outside the work zone, the speed limit for trucks was 10 mph less than that of cars. However, the percentages of speeding trucks were about 19% and 29% higher for treatment and control conditions, respectively, than those of cars.
5.4. Effectiveness of Strobe Lights for Data Set 3

In order to find out whether there were additional speed reductions when the lights were flashing, the net speed reductions were computed using the procedure described in the Study Approach section. The net reductions are summarized in Table 5.3.

Table 5.3
Net Speed Reductions (mph) For Data Set 3

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>Between Station 1 and 2</th>
<th>Between Station 1 and 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Net Speed Reduction</td>
<td>T-test Inference</td>
</tr>
<tr>
<td>Cars</td>
<td>4.87</td>
<td>significant</td>
</tr>
<tr>
<td>Trucks</td>
<td>2.89</td>
<td>significant</td>
</tr>
</tbody>
</table>
Figure 5.8. Cars Exceeding Given Speed
For Data Set 3 When Lights Were Off

Figure 5.9. Cars Exceeding Given Speed
For Data Set 3 When Lights Were On
Figure 5.10. Trucks Exceeding Given Speed
For Data Set 3 When Lights Were Off

Figure 5.11. Trucks Exceeding Given Speed
For Data Set 3 When Lights Were On
5.4.1. Effectiveness of Strobe Lights on Cars

The net speed reduction for cars was 4.87 mph and 7.12 mph at Station 2 and Station 3, respectively. The results of the t-tests indicated that the net reductions are statistically significant. This indicates that the strobe lights additionally reduced the average speeds of cars by 4.87 mph and 7.12 mph.

5.4.2. Effectiveness of Strobe Lights on Trucks

The net speed reduction for trucks at Station 2 was equal to 2.89 mph, and 5.96 mph at Station 3. The results of t-tests show that those differences were statistically significant. Thus, the strobe lights significantly reduced the average speed of trucks at both Station 2 and Station 3.

5.5. Conclusions for Data Set 3

The results from Data Set 3 indicate that the strobe lights on the speed limit signs were effective in reducing the average speed of cars by 4.9 - 7.1 mph, and the average speed of trucks by 2.9 - 6.0 mph inside the work zone. The strobe lights on the speed limit sign not only reduced the average speed of vehicles near the beginning of the one lane section, but also reduced it further down the line in the work zone. Therefore, when the lights were turned on, cars and trucks traveled about 4.9 and 2.9 mph slower before reaching the work space, and 7.1 and 6.0 mph slower after passing the work space. In general, the percentages of vehicles with excessive speeds decreased when the lights were flashing.
CONCLUSIONS

The results from Data Sets 1-3 indicated that the average speed of cars was reduced by 1.9-7.1 mph and that of trucks by 1.3-6.0 mph when the strobe lights on the speed limit signs were flashing. The speed reduction effects were, in general, more pronounced on the cars than on the trucks. Cars and trucks showed net speed reductions before reaching the work space as well as after passing it. The reductions at the location past the work space were 2-3 times more than the reductions at the location before the work space. Cars reduced their speeds, on the average, by 1.9 to 4.9 mph before and by 5.9 to 7.1 mph after the work space. Similarly, the speed reduction for trucks was 1.3-2.9 mph before and 3.3-6.0 after the work space. In general, the percentages of vehicles with excessive speeds in the work zone decreased when the lights were flashing.
REFERENCES


APPENDIX A. DATA REDUCTION

A.1. Procedure

The vehicle speeds at each station were collected with mechanical traffic counters. The traffic counters were IRD Traffic Counter and Classifiers (TCC). These TCC's had a capacity for the attachment of a maximum of four loops and four pneumatic road tubes. The counters were programmed to keep a record of individual vehicles. This was ascertained to be more accurate than having the traffic counter sort the data itself and store it in bins. More information about individual vehicles was available by not grouping them (putting them in bins). The accuracy of measurements was 1 mph for speed, 0.1 ft for axle spacing, and 1 second for time headway. Each TCC has 64K of memory, which can store up to 8,000 individually time-stamped vehicles. The memory of the counter was sufficient for one day of data collection. At the end of each day of data collection, the data was downloaded to an IBM PC using a program called TELECOMP V. The data was stored as an ASCII file on the PC.

A.2. Computer Program

In order to reduce the traffic data to meaningful results, a Fortran program was written to perform sorting and checking tasks on the raw data. The Fortran program, called TRAFFIC, deletes any duplicated entries from the file, separates the data according to lane traveled, computes the headway for successive vehicles in each lane, filters out erroneous data, and separates free flow traffic data from that of platooning vehicles. The following paragraphs briefly describe each of the tasks performed by the TRAFFIC program.

A.3. Duplicate Data

At Station 1 four road tubes were connected to one TCC, when data from both lanes were needed. To collect data in both lanes the pneumatic tubes were used in both lanes, of which one set stretched across one lane, while the other set stretched across both lanes. A vehicle traveling on the outside lane not only triggered the tubes for the outside lane, but also those for the inside lane. As a result, the TCC recorded an entry for the inside lane, which falsely indicated that there was a vehicle on the inside lane.

A.4. Headways

The time headway between successive vehicles was computed. The
time at which each data record was read was converted to seconds, and the difference in time between successive vehicles gave the headway. If the headway was greater than 5 seconds, it was assumed that the vehicle was far enough from the preceding vehicle that it was considered to be traveling at free flow. When the headway was less than or equal to 5 seconds, it was assumed that the vehicle was traveling in a platoon, and therefore was influenced by the leading vehicle. Only free flow vehicles were considered in this study.

A.5. Erroneous Data

A careful review of the raw data indicated that there were occasional erroneous entries. The erroneous data may have occurred when the vehicles were following each other very closely. Erroneous data was also observed at Station 1 when two vehicles in two different lanes went over the tubes at the same time. The erroneous data was considered to be that which met any of the following conditions: very high or very low speeds (less than 30 mph or greater than 100 mph), number of axles greater than 5, very long or very short axle spacings (first axle spacing greater than 40 feet or less than 6.1 feet), and unreasonable axle spacings for a 3, 4 or 5 axle vehicle.

These decisions were made based on review of raw data, truck and car dimensions, axle spacings, axle combinations for trucks, and axle combinations for cars pulling a trailer. The objective was to collect data from those vehicles typically traveling on the highway. For instance, vehicles with more than 5 axles were deleted because they were rare occurrences. Deleting the erroneous data increased the accuracy of the data used for analysis.

A.6. Free-Flow Traffic Data

The data of interest in this study is the free flow traffic data. Consequently, the free flow traffic data was separated based on the time headway as described above.