SAFE AND EFFECTIVE SPEED REDUCTIONS FOR FREEWAY WORK ZONES PHASE 3

Final Report

IMPLEMENTATION RESEARCH

Oregon Department of Transportation

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IMPLEMENTATION RESEARCH

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16. Abstract: Freeway pavement preservation projects typically require construction workers to conduct their work in close proximity to ongoing traffic and often reduce traffic flow to a single lane while work is undertaken in an adjacent lane. During the lane closures, the paving operations place workers on the roadway within a protected work zone. The Oregon Department of Transportation conducted a research study to investigate the impact of 35mph advisory signs, located periodically in the work zone, on vehicle speeds within highway paving project work zones. The research study, which follows two similar studies that addressed other traffic control devices (SPR-751 and SPR-769), centered around one case study on a multi-lane paving project in Oregon. On the case study, the researchers implemented the 35mph advisory signs along with other traffic control devices ("Speed 50" signs with radar speed display, and PCMS signs on rollers) and evaluated the impact of the 35mph signs on vehicle speed and speed variability. The research findings indicate that using the 35mph signs leads to lower vehicle speeds within the work zone. The reduction in speed is greater for passenger cars than for trucks. Use of 35mph advisory signs in future ODOT work zones is recommended to help reduce vehicle speeds through the work zones.

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in	inches	25.4	millimeters	mm	mm	millimeters	0.039	inches	in
ft	feet	0.305	meters	m	m	meters	3.28	feet	ft
yd	yards	0.914	meters	m	m	meters	1.09	yards	yd
mi	miles	1.61	kilometers	km	km	kilometers	0.621	miles	mi
		AREA					**AREA**		
in^2	square inches	645.2	millimeters squared	mm^2	mm^2	millimeters squared	0.0016	square inches	in^2
ft^2	square feet	0.093	meters squared	m^2	m^2	meters squared	10.764	square feet	ft^2
yd^2	square yards	0.836	meters squared	m^2	m^2	meters squared	1.196	square yards	yd^2
ac	acres	0.405	hectares	ha	ha	hectares	2.47	acres	ac
mi^2	square miles	2.59	kilometers squared	km^2	km^2	kilometers squared	0.386	square miles	mi^2
		VOLUME					**VOLUME**		
fl oz	fluid ounces	29.57	milliliters	ml	ml	milliliters	0.034	fluid ounces	fl oz
gal	gallons	3.785	liters	L	L	liters	0.264	gallons	gal
ft^3	cubic feet	0.028	meters cubed	m^3	m^3	meters cubed	35.315	cubic feet	ft^3
yd^3	cubic yards	0.765	meters cubed	m^3	m^3	meters cubed	1.308	cubic yards	yd^3
NOTE: Volumes greater than 1000 L shall be shown in m^3.									
		MASS					**MASS**		
oz	ounces	28.35	grams	g	g	grams	0.035	ounces	oz
lb	pounds	0.454	kilograms	kg	kg	kilograms	2.205	pounds	lb
T	short tons (2000 lb)	0.907	megagrams	Mg	Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)					**TEMPERATURE (exact)**		
°F	Fahrenheit	(F-32)/1.8	Celsius	°C	°C	Celsius	1.8C+32	Fahrenheit	°F

*SI is the symbol for the International System of Measurement

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DISCLAIMER

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1.0 INTRODUCTION

1.1 BACKGROUND

Freeway pavement preservation projects (e.g., pavement overlays, “chip seal” operations, etc.) typically require construction workers to conduct their work in close proximity to ongoing traffic and often reduce traffic flow to a single lane while work is undertaken in an adjacent lane. During the lane closures, the paving operations place workers on the roadway within a protected work zone. In some places the workers only have a line of cones and a few feet, separating them from passing traffic. Areas of limited protection create considerable safety risk for both the workers and passing motorists. Inattentive or speeding drivers, careless workers, misplaced cones, and hazardous roadway conditions can lead to crashes and ultimately work zone injuries and fatalities. The severity of a crash intensifies as the speed of traffic increases *(Aarts and Schagen 2006)*. As a result, preservation projects on high-speed roadways present risk of serious and/or fatal injuries to workers, motorists, and their passengers.

Vehicle speed is directly connected to the performance of work zone designs in preventing accidents. There is a widely held perception that speed is one of the most significant factors in vehicle-related crashes on roadways *(Mahoney et al. 2007)*. However, safely controlling and reducing vehicle speeds through work zones to reduce the risk can be difficult on high-speed roadways. On such roadways, it has been suggested that reducing traffic speeds to 35mph would enhance the safety of the workers and traveling public. However, a reduction in speed from 65mph to 35mph is significant, and evaluation of the impacts of this differential in speed on interstate highways has been limited.

Previous research reveals that work zone speed limit reductions of more than 10mph show an increase in the number of crashes due to a greater speed differential between vehicles *(WSDOT 2009)*. The *Manual on Uniform Traffic Control Devices for Streets and Highways* (MUTCD) *(FHWA 2009)* indicates that a reduction in speed of more than 10mph should be used only when required by restrictive features in the work zone. Where restrictive features justify a speed reduction of more than 10mph, additional driver notification should be provided. The speed limit should be stepped down in advance of the location requiring the lowest speed, and additional traffic control warning devices should be used. These additional safety measures help reduce risk to motorists as they navigate through the active work zone and react to the large difference in speed. In addition, large speed reductions during nighttime work – a time when preservation projects are often conducted – can further complicate the jobsite conditions, be difficult to implement, and may increase risk to worker and motorist safety.

Research on controlling and reducing speeds on high-speed roadways, and on significant speed reductions, has been conducted. In a study of speed reduction measures conducted by Iowa State University on behalf of the Iowa Department of Transportation, the authors state that the most effective speed reduction will probably involve some combination of speed reduction techniques, as opposed to the use of just one type of control measure, although no quantified impact of each independent traffic control measure was provided *(Maze et al. 2000)*. The researchers in Iowa conducted a survey of state transportation agencies and found that only a few agencies even consider reducing speed limits by 20 mph or more. The study also revealed that the use of regulatory speed limit signs and police enforcement is the most common practice for controlling and reducing speeds.

In response to concerns from the Associated General Contractors Oregon-Columbia Chapter and the Oregon Trucking Association about speed through work zones, the ODOT Traffic Roadway Section requested that ODOT Research investigate interstate preservation job safety enhancements. The request, made in the summer of 2011, was to assess the practicality and effectiveness of reducing speeds from 55-65mph to 35mph on highway preservation projects. As an initial step, ODOT conducted a pilot study in September 2011 to investigate practical and safe means for significant speed reductions. The pilot study was conducted on Interstate 5 near Cottage Grove, OR. The traffic control plan included a 30 mph speed reduction from 65 to 35mph implemented in two stages (65 to 50mph, then 50 to 35mph) using multiple OSP officers and other traffic control measures along the roadway prior to and within the work area. This strategy is similar to the use of a system of stepped speed limits (SSL) that was recently studied and recommended in the United Kingdom (ITS International 2011). On the pilot study, with law enforcement vehicles visible to passing motorists, passenger vehicle speed measurements through the work zone showed a mean speed of 33.0mph for cars (n = 108 vehicles; 85th percentile speed = 36mph; 22% of cars exceeding posted speed). For trucks, the mean speed was 33.23mph (n = 145 vehicles; 85th percentile speed = 36mph; 19% of trucks exceeding posted speed).

To augment the pilot study, ODOT has conducted research studies (SPR-751 in FY2013, and SPR-769 in FY2014) to look for ways to safely reduce speeds through work zones on preservation projects taking place on high-speed freeways. The studies focused on four paving projects: I-84 near The Dalles, I-5 just north of the McKenzie River Bridge, I-5 from Glendale to Hugo, and I-5 from Rock Point to Seven Oaks. On each project, different traffic control measures (TCMs) were implemented and speed data was collected both prior to and within the work zone. The TCMs, which were implemented after one treatment with the original traffic control plan (TCP), included:

- “SPEED 50” regulatory signs throughout the work zone
- Portable changeable message signs (PCMS) on pavement rollers or stationary trailers
- Radar speed reader trailers
- Oregon State Police (OSP) patrolling work zone
- OSP parked at end of lane closure taper
- Tubular markers placed on both sides of the live travel lane
- Plastic drums placed on both sides of the live travel lane

In SPR-751 and SPR-769, using the speed data recorded, the reduction in speed from the beginning reference point – "Road Work Ahead" (RWA) signs – to locations within the work zone was calculated along with the speed relative to the distance to the paver. Statistical analyses of the data showed that each TCM helps to reduce the mean speed. The data also suggests a difference in the relative effectiveness of each TCM. The SPR-751 study report was published in February 2013. The link to the SPR-751 report is: http://www.oregon.gov/ODOT/TD/TP_RES/docs/Reports/2013/SPR751_SpeedReductions.pdf.

The SPR-769 study report was published in September 2014, and is available at the following link: http://www.oregon.gov/ODOT/TD/TP_RES/docs/Reports/2014/SPR769_HighSpeed_Final.pdf.

1.2 STUDY OBJECTIVES

The present research was designed to supplement the SPR-751 and SPR-769 studies. The results of both SPR-751 and SPR-769 reveal that the use of multiple TCMs is beneficial to safety in work zones. In addition, the locations in which the TCMs are placed within the work zone are critical to their effectiveness. One additional traffic control device that is of interest is the use of 35mph advisory signs in the work zone. While the regulatory speed through the work zone may be set at 50mph, an advisory 35mph speed may further reduce traffic speeds and could be implemented when roadway conditions are especially hazardous (e.g., on downhill grades or where there is limited space for construction operations to take place). The use of 35mph advisory signs, in combination with other traffic control devices, could become an effective part of TCPs without significant additional effort or expense.

The research includes conducting one additional case study on the I-84 Arlington to Tower Road paving project in a manner similar to the case studies in SPR-751 and SPR-769. The following traffic control measures are used: "SPEED 50" regulatory signs, 35mph advisory signs, PCMS signs on rollers, and radar speed reader trailers. The major focus of this research study is to explore the effectiveness of the 35mph advisory signs. The specific objectives for this research study are to:

1. Implement the selected traffic control measures on the I-84 Arlington to Tower Road paving project;

2. Compare the performance of the implemented treatments based on their ability to lower speeds a significant amount and ability to minimize speed variability; and

3. Develop guidance for ODOT and construction contractors to reference when planning and implementing traffic control measures on highway preservation projects.

2.0 CASE STUDY PROJECTS

2.1 TRAFFIC CONTROL MEASURES (TCMS)

The traffic control measure (TCM) of interest for this study is the 35mph advisory signs. Figure 2.1 shows an example of a 35mph advisory sign used in the study. Four 35mph signs were used during each night of paving, spaced approximately 0.5 miles apart. The first sign was located approximately 0.5 mile downstream of the beginning of the work. The second sign was located 1 mile downstream of the beginning of the work. The 3rd and 4th signs were placed at 1.5 and 2 miles from the beginning of the work, respectively.

Figure 2.1: 35mph signs on roadway

For this study, speed sensors placed in the roadway to collect traffic data were located adjacent each 35mph sign. The placement of the signs and the speed sensors along the length of the work zone is shown in Figure 2.2.

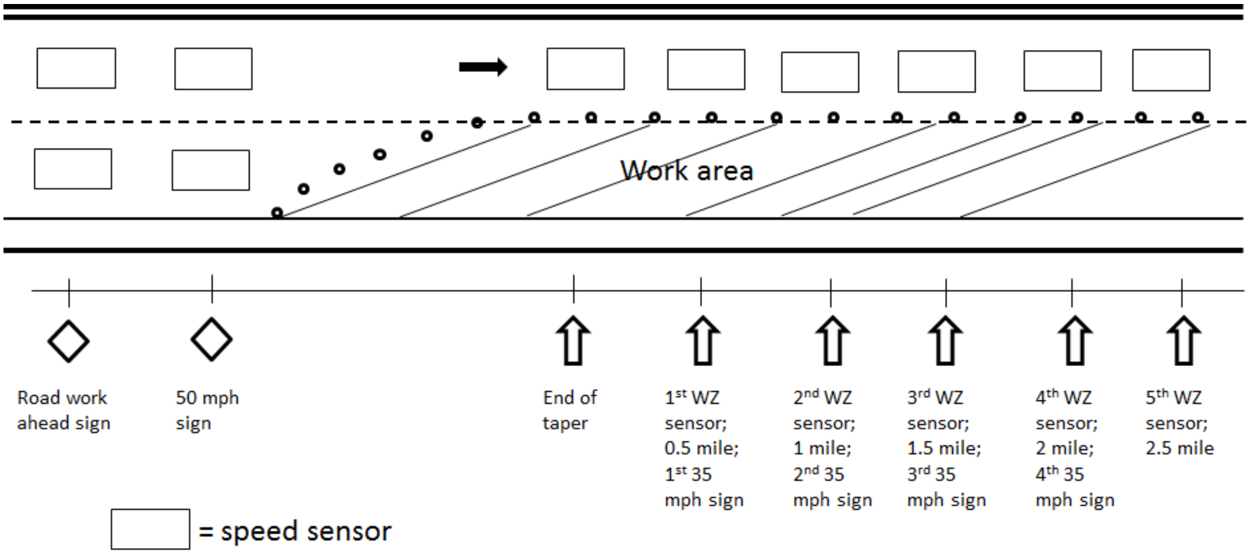

Figure 2.2: Layout of speed sensors and traffic control measures

2.2 CASE STUDY: I-84 ARLINGTON TO TOWER ROAD PROJECT

The case study project selected for this research was the I-84 Arlington to Tower Road project. The project was located at a rural area along the Columbia River. At the location of the project, the roadway is mostly flat and straight. There were no perceived issues related to roadway grade or curves. The location of the project is shown in Figure 2.3.

Figure 2.3: Location of the I-84 Arlington to Tower Road project

At the location of the project, the roadway consists of two lanes in each direction (eastbound and westbound). The project extended for 21 miles from MP 138 to MP 159. The paving scope of work consisted of grinding 2 inches of existing highway surface and placing a new layer of asphalt in both the slow lane and fast lane. Both lanes are 14 feet wide. A paved shoulder is present, but no shoulder paving was included in the project. The paving work activities took place at night, typically from approximately 7:00pm until 5:00am the next morning.

The project was separated into two stages of work by the contractor. The first stage consisted of paving from Arlington Road (MP 138) to Exit 147 (MP147), and the second stage covered the distance from Exit 147 (MP 147) to Tower Road (MP 159). Due to their lack of availability at the start of the project, the researchers were not able to start collecting data at the beginning of the paving work. By the time when the researchers were able to visit the jobsite to collect data, the first stage of the work had already finished. The first day of data collection occurred during the second stage of work, and was on the last day of slow lane paving of the second stage.

During the first stage of the work, while no research data was collected, a variety of traffic controls were implemented according to the TCP for the project. These included the 50mph regulatory signs, radar speed display with 50mph signs, and PCMS signs on rollers.

Table 2.1 shows the data collection matrix for the case study during the second stage of the work. The standard traffic control measurements used for each day were 50mph regulatory signs, radar speed display with 50mph signs, and PCMS signs on rollers. Data collection took place on all of the work days included in the second stage of the work.

On Day 3, 35mph signs in the work zone were added to the work zone together with a radar speed display board. However, due to technical issues, the radar speed display was not working and required repairs. As a result, the radar speed display was not used by the contractor for the remaining days. In order to provide an additional control day for comparison, the researchers decided not to place the 35mph advisory signs on Day 7.

Placement and removal of the speed sensors took place in a manner similar to that conducted for SPR-751 and SPR-769. For further information about the data collection process, please refer to the SPR-751 and SPR-769 research reports.

The project and data collection went very smoothly. On some days, the contractor managed to pave four miles. However, not every day was the same. Table 2.2 provides detailed information regarding the operation on each day. The table also shows the actual range and time span of the paving operation.

As noted in Table 2.2, on Day 2 the contractor paved 0.8 miles of the westbound slow lane, then moved the work operation to paving the eastbound fast lane. The added traffic control measures (50mph regulatory signs, PCMS on rollers, and radar speed display) and the speed sensors for data collection were placed on the eastbound direction only. Similarly, the contractor split the work between the eastbound direction and then the westbound direction on Day 6. The speed sensors were placed in the westbound direction only.

Table 2.1: Data collection matrix

Testing Day	**Paving lane (FL, SL)**	**Traffic Direction (Eastbound, Westbound)**	**Milepoints**	**Date and Day of Week**	**Treatments**				
					A	**B**	**C**	**D**	**E**
					50 mph speed signs	**Radar speed display with 50mph signs**	**PCMS on rollers**	**35mph advisory signs**	**Radar speed display with 35mph advisory signs**
Day 1	SL	Westbound	MP 151.5-147.5	6/17, Tuesday	●	●	●		
Day 2	FL	Eastbound	MP 147-149	6/18, Wednesday	●	●	●		
Day 3	FL	Eastbound	MP 149-152.5	6/19, Thursday	●	●	●	●	●*
Day 4	FL	Eastbound	MP 152.5-155.5	6/23, Monday	●	●	●	●	
Day 5	FL	Eastbound	MP 155.5-158.5	6/24, Tuesday	●	●	●	●	
Day 6	FL	Westbound	MP 159-158	6/25, Wednesday	●	●	●	●	
Day 7	FL	Westbound	MP 158-155	6/26, Thursday	●	●	●		
Day 8	FL	Westbound	MP 151-147	6/29, Sunday	●	●	●	●	

* Radar speed display not operable.

Table 2.2: Work zone elements and paving locations

Testing Day	Work Zone Element Locations (milepoints)								Paving		Notes/Comments
	RWA signs	50 mph signs	End of taper	1st WZ sensor	2nd WZ sensor	3rd WZ sensor	4th WZ sensor	5th WZ sensor	Direction (EB, WB) and Location (milepoints)	Time	
Day 1	152.9	152.55	151.65	151.2	150.65	150.15	149.65	149.10	WB 151.55-147.70	7:33pm-6:16am	• Taper location moved at 3:00am due to the long length of the work zone (4 miles long); • 50mph signs remained at the same location, and pulled off road at 6:00am
Day 2	145.60	146.05	146.85	147.5	148	--	--	--	WB 147.68-147.08 EB 147.05-148.84	9:23pm-11:19 11:47pm-6:13am	• Paved ramps before 9:30pm, then westbound slow lane for 0.8 miles, then moved to paving eastbound fast lane; • Speed sensors and 50mph signs were put on eastbound only.
Day 3	147.3	--	148.6	149.25	149.75	150.3	150.8	151.3	EB 148.86-152.11	7:47pm-5:37am	• 35mph radar trailer put between 1st and 2nd 35mph signs. Trailer moved 4 times during the night. It was out of work area the whole time.
Day 4	150.65	151.05	152	152.65	153.15	153.65	154.1	154.65	EB 152.12-155.33	7:40pm-6:11am	
Day 5	153.9	154.15	155.2	155.85	156.35	156.85	157.35	157.85	EB 155.35-158.29	7:44pm-5:58am	
Day 6	156.8	156.3	159.4	158.75	158.25	157.75	157.25	156.75	EB 158.30-159.29 WB 159.25-157.99	7:45pm-11:22pm 11:38pm-3:57am	• All speed sensors put down on westbound only; • Sensors picked up at 4:00am due to rain.
Day 7	159.5	159	158.15	157.55	157.05	156.55	156.05	155.55	WB 157.99-155.17	7:44pm-4:44am	• Speed sensors picked up at 5:00am due to rain.
Day 8	153	152.7	151.8	150.7	150.2	149.7	149.25	148.75	WB 151.23-147.10	7:30pm-6:25am	

3.0 RESULTS

3.1 INTERVIEW RESULTS

During the work shifts on the days of data collection, the researchers interviewed contractor and ODOT personnel on the jobsite about the impacts of the 35mph advisory signs. The interviews consisted of asking the participants several open-ended questions about the 35mph advisory signs, including the perceived impact of the signs on vehicle speeds, the visibility of the signs, placement of the signs, and suggestions for alternative location and configuration. Those interviewed were also asked about their general impression of the traffic control in the work zone.

A total of 12 people were interviewed. Those interviewed consisted of 9 contractor personnel (2 quality control personnel, 3 asphalt truck drivers, 1 tack truck driver, 1 water truck driver, 1 grinder operator, and 1 traffic control crew member) and 3 ODOT personnel (2 inspectors and 1 quality control personnel).

Some of those interviewed felt that the 35mph signs were effective in slowing down the traffic, while others thought that the signs did not impact vehicle speed. Those interviewed mentioned that they were happy to see the signs, knowing that something was being done to slow vehicle speeds and help improve safety. Those interviewed also mentioned that they paid attention to the signs, however they felt that the general public may not be aware of the nature and meaning of the signs (compared to regulatory signs).

For this project, the roadway condition enables the implementation of the signs due to a wide shoulder on both sides of the roadway. The roadway could have accommodated more signs. One of the personnel interviewed suggested that more signs are needed, and that the signs should be placed on both sides of the road rather than on only one side. The project is at a windy location, and flexible stands (as shown in Figure 2.1) were selected for use.

The placement of the 35mph signs takes only minimal effort. Approximately 1 minute per sign, plus driving time between sign locations, is required. It took two workers with one truck to put out all of the flexible signs. The signs cost approximately $14 per square feet.

3.2 DATA ADJUSTMENT AND RE-CALIBRATION OF SPEED SENSORS

To ensure a high level of accuracy in the case study results, two sensor validation tests were conducted as part of SPR-769 after collecting the data for the case studies. The results of the validation tests are presented in the SPR-769 final report. The results of the validation tests were found to be an acceptable way of calibrating the sensors, and the process was repeated for the present study to maintain accuracy.

For the present study, the researchers tested the speed sensors before and after using them on the I-84 Arlington to Tower Road project. The validation tests consisted of the researchers driving past all of the sensors at speeds ranging from 30 to 60mph (30, 35, 40, 45, 50, 55, and 60 mph). Three passes were made at each speed. The results of the before and after validation tests were very similar. In addition, the results of the tests showed a trend similar to that found in the SPR-769 study. Adjustments were required for sensors 103, 105, and 106. Therefore, the same equations that were developed in SPR-769 to convert the recorded speed to the actual speed were also used for these sensors in the present study.

3.3 SPEED DATA SUMMARY

Figure 3.1 shows a summary of the 85th percentile speed of all of the vehicles on each day at each sensor location. As seen in the figure, the speeds at the Road Work Ahead sign, 50mph signs, and end of taper locations are very similar for the different days. For the speed through the work zone, the figure reveals that the 85th percentile speeds on Day 1 and Day 7 (without the 35mph signs) are higher than on Days 3, 4, 5 and 8 (with 35 mph signs). Days 2 and 6 are unique in that the paving operation occurred in two directions on those days. Part of the paving occurred in one direction during the first part of the work shift, and then the work switched to paving the roadway in the other direction (see Table 2.2).

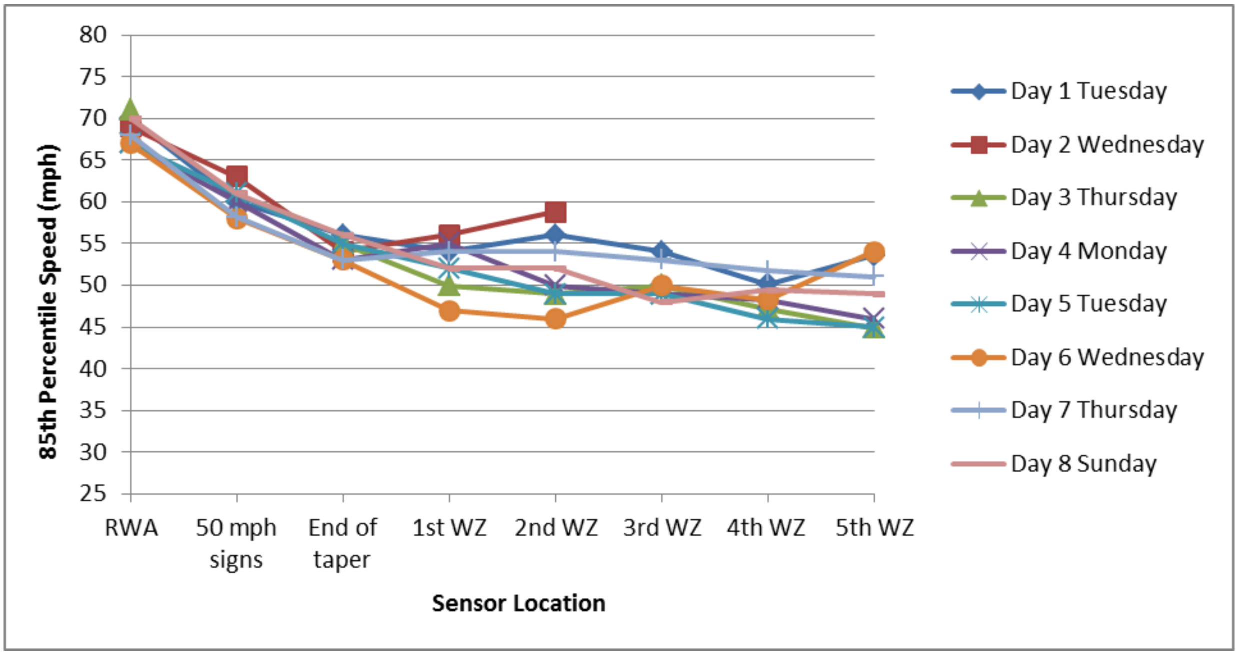

Figure 3.1: 85th percentile speed for each day at different locations

The figure also shows that vehicle speed changes throughout the work zone. At the Road work Ahead (RWA) sign location, the 85th percentile speed was recorded to be typically from 65-70mph. After the vehicles pass by the RWA sign location, the speed then drops to approximately 60mph as the vehicles pass the 50mph regulatory signs. At the end of taper location, the speed drops to 55mph, and in the work zone the 85th percentile speed on each day is approximately 50mph.

On Days 2 and 6, as described above, for a portion of the work shift the paving work took place on the opposite side of the roadway than the speed sensors. While the work is taking place in one direction, the drivers travelling in the opposite direction may slow down to watch the work taking place in the opposite direction (“rubber-neck”). Rubber-necking may be significant if the median width is small, and when the paving work is taking place in the fast lane in one direction while the motorist is travelling in the fast lane in the other direction. This impact may be a confounding factor in the speed data on Days 2 and 6. On both days, the overlap in work took place at locations where the median width was not a great distance.

Figure 3.2 shows the hourly 85th percentile speed for each day at the RWA location. As can be seen in the figure, there is no apparent difference in speed from day to day, and just a slight difference throughout the course of the work shift. This result is expected as the RWA locations are well upstream of the work zone, and the volume of traffic each day was low enough such that it was not a significant impacting factor. In addition, at the RWA location it is assumed that the speeds on each day are typical for that particular day of the week. For example, the speeds recorded on a Monday are similar to those speeds on the Monday of the previous week. There are no immediately identifiable impacting factors that would indicate the speeds would be different.

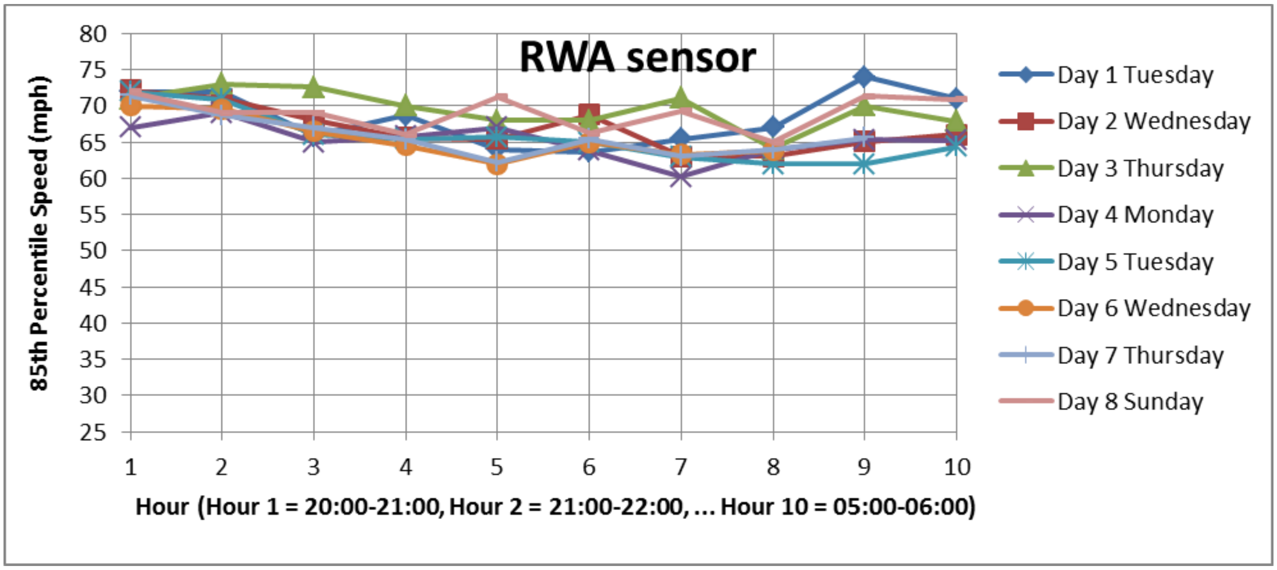

Figure 3.2: 85th percentile speed of each hour for each day at RWA location

Figure 3.3 shows the hourly 85th percentile speed for each day at the end of taper location. Similar to the RWA location, there is no apparent significant difference from day to day. The speed during the last hour on Day 1 is very high and is an outlier. On Day 1 the contractor paved a very long distance (4 miles) and moved the taper location to the end of work zone during the last hour. Therefore, given that the sensors were not relocated, the speeds recorded at that location during the last hour reflected speeds when the taper was not present. At the RWA location, for the last hour (05:00-06:00) the 85th percentile speed was approximately 70mph on Day 1, while at the end of the taper the 85th percentile speed was approximately 75mph during the same hour. The absence of a taper due to its relocation may have impacted this difference in speed. That is, after seeing the RWA signs, motorist may tend to speed up if they do not see a taper or other traffic control device after driving a short distance downstream. Periodic reminders may be needed.

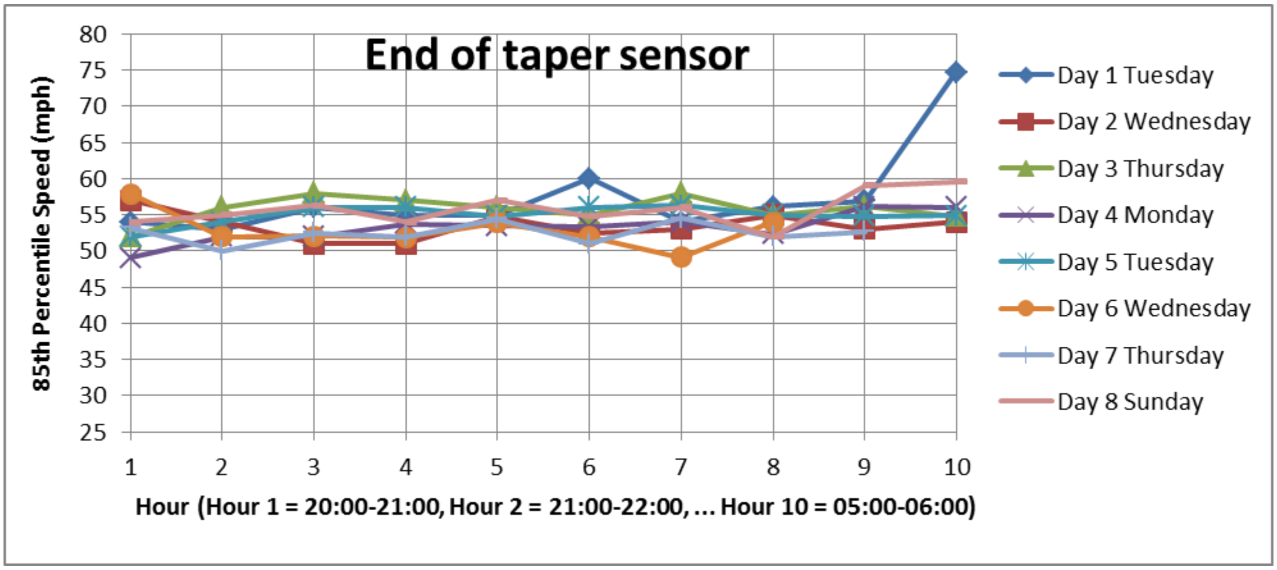

Figure 3.3: 85th percentile speed of each hour for each day at end of taper location

Figure 3.4 shows the hourly 85th percentile speed for each day at the 1st work zone (WZ) sensor location. As seen in the figure, the general trend for the speeds on each day is an increase in speed during the course of the work shift. The figure shows that Days 2 and 6 are different than the other days. On Days 2 and 6, the paving operation started in the westbound (or eastbound) direction and switched to the eastbound (or westbound) direction at approximately 11:30pm. One confounding factor on Days 2 and 6 may be the relocation of the equipment to the other direction. As the equipment is moved into location, and traffic control measures placed, the motorists may tend to slow down to watch the mobilizing operation.

Data collection also ended at different times on different days due to weather conditions. On Days 6 and 7, it started to rain in the morning hours later in the work shift. As a result, data collection on Day 6 ended at 4:00am, and on Day 7 at 5:00am. The weather conditions may have impacted the speeds during the morning hours later in the work shift on these days.

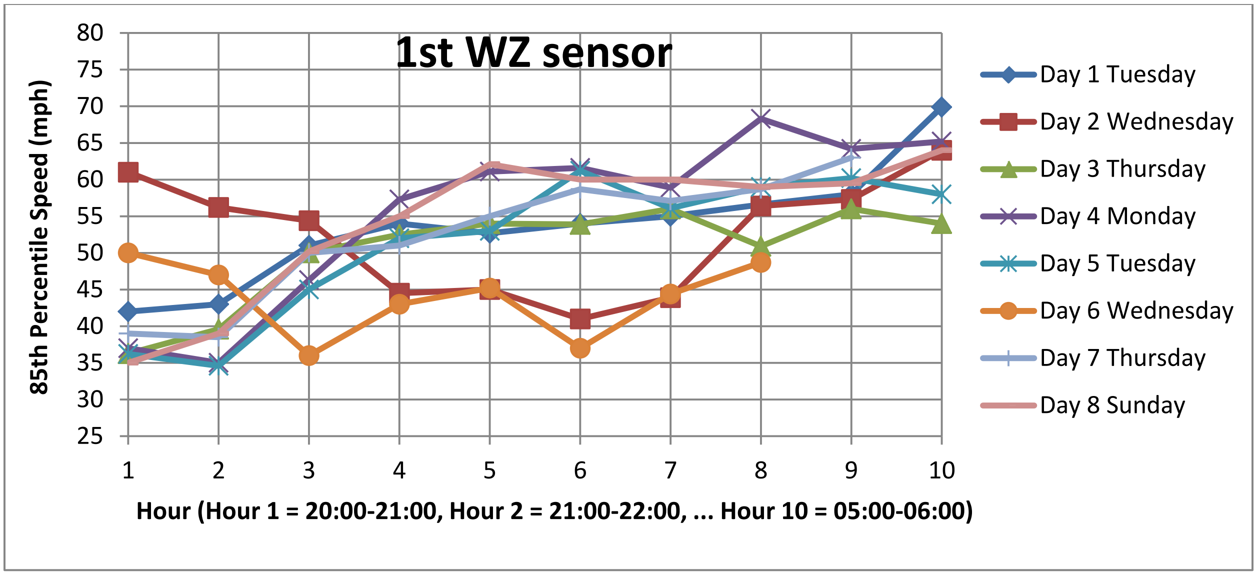

Figure 3.4: 85th percentile speed of each hour for each day at 1st WZ sensor location

The next figure (Figure 3.5) shows the traffic volume of each hour for each day. The traffic count is based on the vehicles recorded at the end of taper sensor. There is a clear trend of decreasing traffic volume from 8:00pm to 1:00am. After 1:00am, the hourly traffic volume is lower than 100 for most of the days. The recorded volumes only count the vehicles during the work shift; the total volumes for the entire day will be greater.

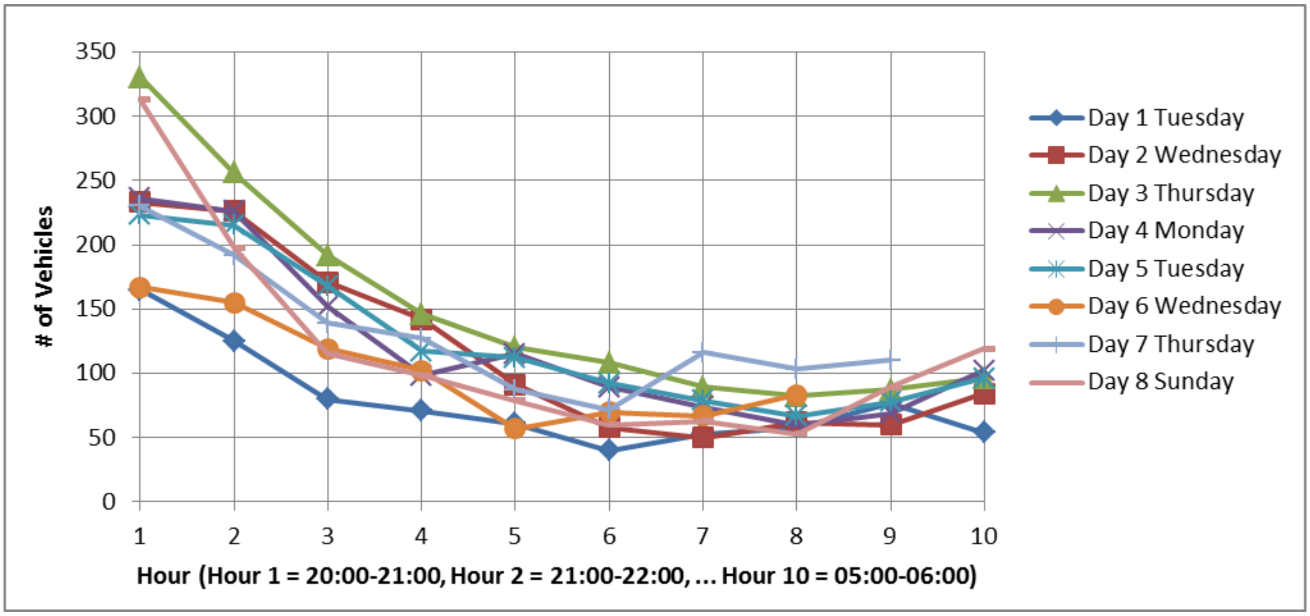

Figure 3.5: Traffic volume of each hour for each day at end of taper location

Figure 3.6 shows number of trucks and passenger cars for each day during the work shift. For this chart, passenger cars are classified as those vehicles that were 25 feet or less in length. Trucks are classified as those vehicles that were greater than 25 feet in length. The portion of trucks relative to that of passenger cars is high due to the low overall traffic volume and the presence of the asphalt trucks. The asphalt trucks, which would not be present without the work zone, contribute to the relatively large truck volume.

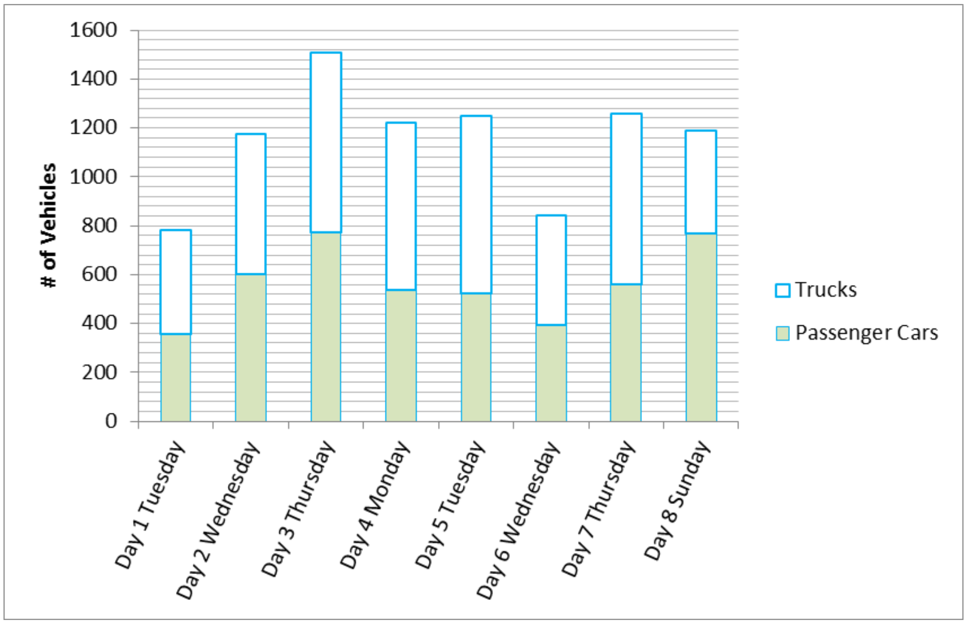

Figure 3.6: Traffic volume for different types of vehicles for each day

4.0 ANALYSIS

4.1 DISTANCE TO PAVER ANALYSIS

Observations of motorist behavior on the case study projects during the SPR-751 and SPR-769 studies revealed that motorists would slow down when they approached the paver and speed up after they passed the paver. This change in speed was also observed when vehicles passed the grinder. This decrease in speed while passing the equipment was confirmed in the analysis of the speed data in SPR-751 and SPR-769.

Vehicle speed near the paver and grinder are a major concern of the present research study also given that many workers are on the ground in the vicinity of these pieces of equipment. As a result, knowing how the different traffic control devices affect the vehicle speed around the paver and grinder is very important. (Note: For this analysis, only speeds relative to the paver are presented and analyzed. The change in vehicle speeds relative to the distance to the grinder is assumed to be similar to the change relative to the paver.)

The speed sensors used to record the speed data were placed on the ground at fixed locations. The paver, on the other hand, is constantly moving as part of the paving operation. The passing vehicles are also moving. As a result, it is difficult to determine the relationship between vehicle speed and distance to paver by direct measurement for each passing vehicle. Therefore, the researchers used an indirect approach. The speed sensors recorded vehicle speed, vehicle length, and the time when the vehicle passed the sensor. As part of the construction operations, a construction worker (ticket taker) is assigned to take asphalt volume amounts directly from the asphalt truck drivers. The ticket taker also records the time in which the asphalt truck dumps its load in front of the paver and the location of the truck when it dumps its load. Using this information, the researchers know the approximate location of the paver from the ticket taker's forms (a few feet behind the dumping point) and the time in which the paver was at the location. The location of the speed sensor on the roadway is also recorded prior to the start of the work shift. As a result, the distance between the paver and speed sensor can be calculated at any time and for each vehicle that passes over the sensor.

Vehicle speed relative to the distance to paver was calculated for each day at the 3rd sensor in the work zone. Figure 4.1 shows a summary of the distance to paver graphs for all of the days of testing for all vehicles, based on the 3rd WZ sensor, excluding Days 2 and 6. Days 2 and 6 were not included in this graph due to the different conditions of these two days as described above. The time in which the paver passed the 3rd WZ sensor on each day is shown in the labels for each day. The figure shows that vehicles slow down to approximately 35mph when they pass the paver. The slowdown starts approximately 0.6 miles upstream of the paver. After passing the paver, the vehicles then speed up slightly downstream of the paver. The increase in speed takes place over approximately 0.2 miles, after which the speed levels off for another 0.6 miles. The constant rate of speed (at approximately 40mph) is likely a result of the vehicles passing by the downstream equipment (tack truck, sweeper, grinder, etc.). The speed trends for different days are similar.

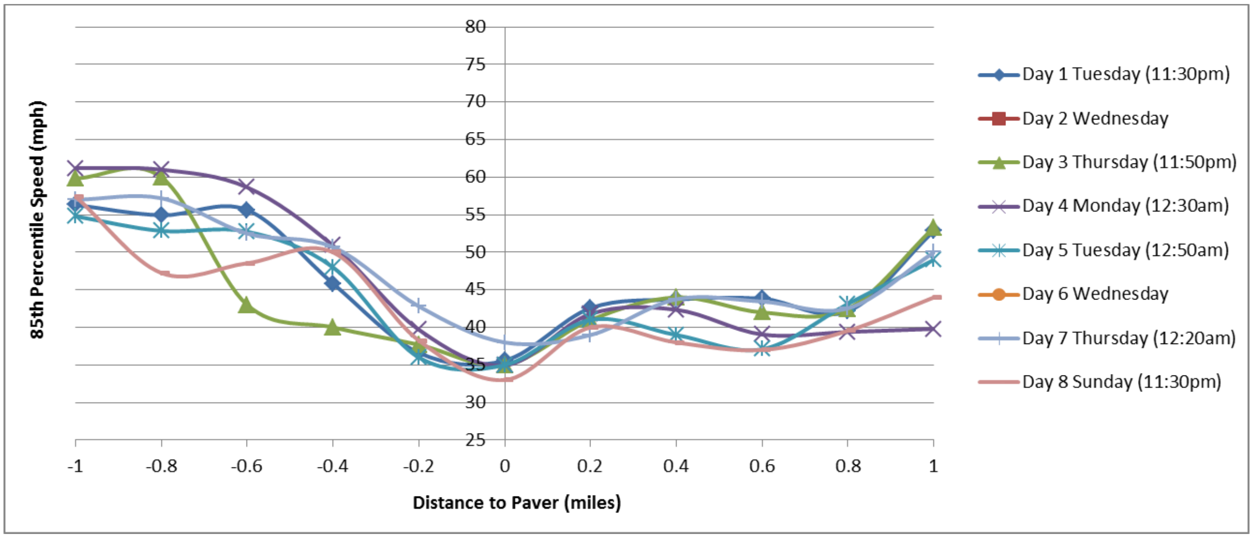

Figure 4.1: Distance to paver graph for each day based on 3rd WZ sensor

As seen in Figure 4.1, on Day 3 vehicle speeds decreased significantly approximately 0.6 miles upstream of the paver. The rate and location of decrease are different for this day than the other days. On Day 3, the radar speed display trailer with 35mph advisory sign attached was initially located between the 1st and 2nd 35mph signs. The trailer was then moved downstream four times during the work shift. At the time in which the paver passed the 3rd work zone sensor on Day 3 (11:50pm), the radar speed trailer may have been placed near, or just downstream, where the significant decrease in speed is seen in the figure. The presence of the radar speed display plus the paver up ahead may have caused the drivers to slow down sooner than on other days.

Figure 4.2 shows the 85th percentile speed of all vehicles during the hour from 12:00 – 1:00am of Day 5 at different locations in the work zone. The figure depicts the speed of a group of vehicles (i.e., those traveling through the work zone from 12:000-1:00am on Day 5) as the vehicles pass through the work zone. The figure reveals that at the RWA location, the majority of vehicles traveled at about 65mph. When they reached the 50mph regulatory signs, which are located approximately 0.3 miles downstream of the RWA signs, their speed dropped to 59mph. When the vehicles reached the end of taper location, the speed dropped to 55mph. At that time, the paver was at approximately the 3rd WZ sensor location. When the vehicles passed the 1st WZ sensor, they were approximately 1 mile from the paving operation and their speed was about 53mph. When they got closer to the paver (at the 2nd WZ sensor about 0.5 mile before the paver), their speed dropped to 41mph. They pass paver at a speed of 38 mph. After passing the paver, the speed was maintained at approximately 37mph through the rest of the work zone. The relatively constant speed following the paver likely was due to the presence of the additional equipment (e.g., tack truck, sweeper, and grinder) ahead of the paver. As the vehicles passed this additional equipment, they keep a low and constant speed.

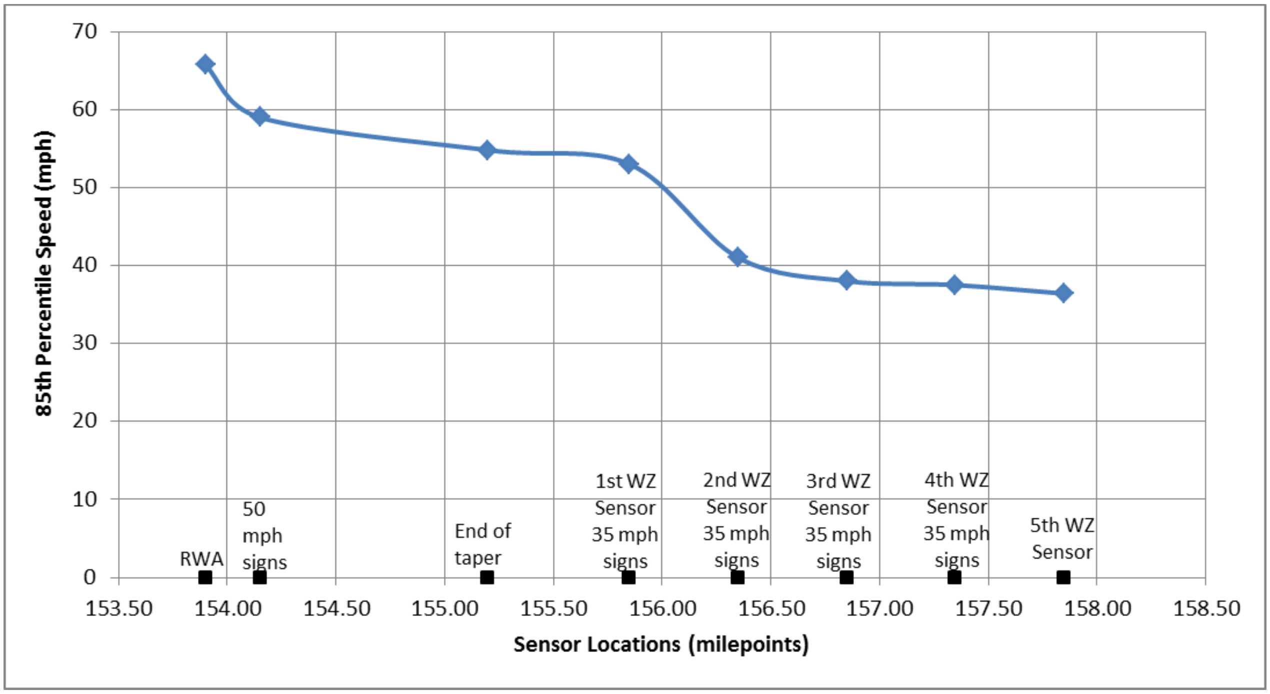

Figure 4.2: 85th percentile speed during hour 12:00-1:00am of Day 5 at different locations

4.2 STATISTICAL ANALYSIS OF VEHICLE SPEEDS

Statistical tools are used to evaluate the treatment effectiveness and compare speed difference among days. As discussed above, Day 2 and Day 6 are different than the other days. As a result, the data from Days 2 and 6 is not included in the statistical analysis.

Table 4.1 shows the 85th percentile speed of passenger cars and trucks at the RWA sign location for each day. The table also shows the total volume of vehicles (passenger cars and trucks) during the data collection period. A portion of the total truck volume consists of asphalt trucks. The approximate asphalt truck volume is shown in the table. Asphalt truck volume is calculated from the tally sheet provided by the ticket taker that documents the number of trucks dumping asphalt in front of the paver each day. It is assumed that the number of asphalt trucks used for the grinding operation is the same as that used for dumping new asphalt. The approximate asphalt truck volume shown in the table represents both those trucks dumping new asphalt and those trucks accepting old asphalt from the grinder.

Table 4.1: Volume and 85th percentile speed for different types of vehicles at RWA sign location

Test Day	Passenger cars		Trucks				Total vehicle volume
	85th% speed (mph)	Volume	85th% speed (mph)	Asphalt truck volume (approximate)	Through truck volume	Total truck volume	
Day 1	73	376	60	304	154	458	834
Day 3	73.1	675	62	292	245	537	1212
Day 4	72	546	59	290	301	591	1137
Day 5	72	541	62	300	309	619	1160
Day 7	72	498	60	236	327	563	1061
Day 8	72	701	62	304	113	417	1118

Table 4.1 reveals that the 85th percentile speed for passenger cars before entering the work zone is approximately 72mph each day, while the speed for trucks is around 60mph. These speeds are fairly consistent from one test day to the next test day. In addition, the volume of passenger cars is not much different than the volume of trucks. However, the data suggests that a large portion of trucks are asphalt trucks working for the project. As a result, the asphalt truck speed may have a big impact on overall truck speed. Insufficient data is available to accurately determine the 85th percentile speed of just the asphalt trucks (the speeds of the asphalt trucks cannot be separated from the speeds of the other trucks in the raw data).

Table 4.2 shows the mean speed and standard deviation of the passenger cars and the trucks at the RWA sign location. This table shows that not only passenger cars have higher speed than trucks, but also the standard deviation of the passenger car speeds is higher than the standard deviation for trucks.

Table 4.2: Mean speed and standard deviation for different types of vehicles at RWA sign location

Test Day	Passenger cars		Trucks	
	Mean speed (mph)	Standard deviation	Mean speed (mph)	Standard deviation
Day 1	64.2	9.7	55.2	6.6
Day 3	65.0	9.2	56.8	6.3
Day 4	63.3	8.4	54.0	5.5
Day 5	63.0	10.3	56.0	6.5
Day 7	63.4	8.7	55.1	5.9
Day 8	62.9	10.0	56.3	8.5

Table 4.3 shows the 85th percentile speed of each day at the 50 mph sign location. Day 3 did not include sensors at this location, so there is no data for that day at this location. The 85th percentile speeds for both passenger cars and trucks are consistent from day to day. The 85th percentile speed for passenger cars was approximately 64mph, and for trucks approximately 55mph. The distance from the RWA sign location to the 50mph signs is different for different days, mostly in the range of 0.3 mile to 0.5 mile (see Table 2.2). When comparing the speeds

shown in Table 4.3 to those shown in Table 4.1 (at RWA sign location), it is clear that both passenger cars and trucks slow down by approximately 10mph between these two locations.

Table 4.3: 85th percentile speed for different types of vehicles at 50mph sign location

Test Day	Passenger cars 85th% speed (mph)	Trucks 85th% speed (mph)
Day 1	62	56
Day 3	--	--
Day 4	65	55
Day 5	65	56
Day 7	63	55
Day 8	64	55

The mean speed and standard deviation for different types of vehicles at the 50mph sign location is shown in Table 4.4. Similar to the RWA sign location, truck speed and standard deviation are lower than those of passenger cars. For both passenger cars and trucks, the mean speed and standard deviation are consistent from day to day, except on Day 7 when the trucks have a lower speed but higher variance than the other days. The result on Day 7 is likely due to the fact that the 50mph signs and adjacent speed sensors were placed immediately downstream of an on-ramp. The asphalt trucks, along with other vehicles, likely used that on-ramp to access the work zone frequently.

Table 4.4: Mean speed and standard deviation for different types of vehicles at 50mph sign location

Test Day	Passenger cars		Trucks	
	Mean speed (mph)	Standard deviation	Mean speed (mph)	Standard deviation
Day 1	52.4	10.4	49.3	7.6
Day 3	--	--	--	--
Day 4	55.0	9.1	49.3	6.7
Day 5	56.1	8.8	50.9	6.6
Day 7	52.3	9.9	47.1	9.2
Day 8	54.5	9.3	49.2	7.1

Similar to the tables shown above, Table 4.5 and Table 4.6 show the speeds (85th percentile and mean) and standard deviation for the different types of vehicles at the end of taper location for each day. At this location, the speeds for passenger cars are still higher than for trucks, but only approximately 3mph higher. At the end of taper location, both passenger cars and trucks have 85th percentile speed between 50 and 60mph.

Table 4.5: 85th percentile speed for different types of vehicles at end of taper

Test Day	Passenger cars 85th% speed (mph)	Trucks 85th% speed (mph)
Day 1	57	55
Day 3	58	54
Day 4	54	51
Day 5	58	53
Day 7	54	52
Day 8	56	53

Table 4.6: Mean speed and standard deviation for different types of vehicles at end of taper

Test Day	Passenger cars		Trucks	
	Mean speed (mph)	Standard deviation	Mean speed (mph)	Standard deviation
Day 1	49.4	10.1	47.5	9.7
Day 3	49.6	8.8	47.7	7.1
Day 4	47.2	8.1	46.1	6.3
Day 5	49.2	8.9	47.5	6.7
Day 7	46.2	9.6	45.7	8.1
Day 8	49.9	7.6	48.5	7.4

The 85th percentile speed for vehicles while traveling in work zone adjacent the work area is shown in Table 4.7. The work zone speed is calculated using the speeds recorded by the first four sensors in work zone. Similarly, Table 4.8 shows the mean speed and standard deviation for different types of vehicles for each day in the work zone, based on the first four sensors in the work zone.

Table 4.7: 85th percentile speed for different types of vehicles in work zone (first four WZ sensors combined)

Test Day	Passenger cars 85th% speed (mph)	Trucks 85th% speed (mph)
Day 1	54	53
Day 3	48	50
Day 4	47	54
Day 5	46.7	51
Day 7	52	53
Day 8	46	54

Table 4.8: Mean speed and standard deviation for different types of vehicles in work zone (first four WZ sensors combined)

Test Day	Passenger cars		Trucks	
	Mean speed (mph)	Standard deviation	Mean speed (mph)	Standard deviation
Day 1	41.7	13.0	40.0	12.2
Day 3	37.4	11.1	39.7	10.8
Day 4	36.0	11.1	40.4	12.2
Day 5	36.2	10.5	39.2	11.1
Day 7	39.8	11.8	41.3	11.7
Day 8	36.0	11.2	40.7	12.9

It can be seen from Table 4.8 that in the work zone, unlike at other locations, the standard deviations of passenger cars and trucks were similar in magnitude. In addition, on all but one day, passenger cars had lower work zone speeds than trucks. Considering Day 1 and Day 7 were the days without the 35mph advisory signs present and the other days were with 35mph signs present, the difference in mean speeds (between Days 1 and 7 and the other days) may be due to the traffic control measurement of interest – the 35 mph signs. When just focusing on passenger cars, in addition to the mean speeds on Days 1 and 7 being greater than on the other days, the standard deviations on Days 1 and 7 were also greater (i.e., there was greater variation in the speeds on Days 1 and 7 compared to the other days). This same trend is not present for the trucks.

To determine the effect of the 35mph advisory signs on vehicle speed, a two-sample t-test is used to compare the speed when using 35mph signs to the speed without the 35mph signs present. In this analysis, the data from 13,474 passenger cars and 12,198 trucks is included. This amount of data represents more than the overall traffic volume during the work shift. There are four sensors in the work zone and, therefore, the data includes four different work zone speeds for every vehicle.

The results show that for all vehicles combined (both cars and trucks together), the mean speed with the 35mph signs present was 2.65 mph lower than the mean speed without the 35mph signs present (p-value $< 2.2\ e^{-16}$). The 95% confidence interval for this difference is 2.33 to 2.97 mph.

When the passenger cars and trucks are analyzed separately, the mean speed and difference are shown in Table 4.9.

Table 4.9: Effect of 35mph advisory signs on vehicle speed

Type of vehicle	Mean speed (mph) without 35mph signs (Days 1 and 7)	Mean speed (mph) with 35mph signs (Days 3, 4, 5, and 8)	Difference in mean speeds (mph)	p-value
Passenger cars	40.58	36.41	4.18	$< 2.2\ e^{-16}$
Trucks	40.72	39.93	0.79	0.00059

Table 4.9 reveals that for both cars and trucks the difference in the mean speed between the days with and the days without the 35mph signs is statistically significant. For both types of vehicles, the vehicles tend to drive slower with the 35mph signs present. The effect of the 35mph signs was greater on passenger cars than on trucks. The mean speed for passenger cars with the 35mph signs is 4.17 mph lower than the mean speed without the 35mph signs present, while for trucks, the difference is only 0.79 mph. There are many possible reasons for the difference between passenger cars and trucks. Since a large portion of trucks are asphalt trucks working for the project, this result may suggest that asphalt truck drivers pay little attention to the signs since they are knowledgeable of the work zone and may pass through it multiple times in a work shift and many times during the course of the construction work. Another reason may be because truck drivers know the 35mph signs are advisory signs, rather than regulatory, so they do not pay as much attention to the 35mph signs.

4.3 ANALYSIS OF SPEED DIFFERENCE AND DISTANCE BETWEEN ADJACENT VEHICLES

The next part of the analysis consisted of focusing on the difference in speed between vehicles next to each other and the distance between the vehicles. The speed difference between adjacent vehicles is a concern if the difference is large. A faster vehicle approaching a slower vehicle may increase the risk of rear-end crashes. Slow vehicles relative to other nearby upstream vehicles may also create a “shock-wave effect” in the work zone and possible queuing if extremely slow. In addition, a vehicle that travels too closely behind another vehicle creates a rear-end crash hazard. For this analysis, the researchers calculated the speed difference and distance between adjacent vehicles, and then made statistical comparisons to determine whether the 35mph advisory signs had an impact on the speed difference and distance apart.

Table 4.10 shows the speed difference and estimated distance between adjacent vehicles for a sample of ten vehicles at approximately 8:00pm on Day 5 (with the 35mph advisory signs present). Day 5 was selected to illustrate the data analysis because on that day the paving operations and traffic were representative of typical conditions expected on the roadway. The time of day (8:00pm) was targeted because the paving work was still relatively close to the taper, radar speed display, and 50mph regulatory signs. The first column of the table indicates the vehicle number, according to the time stamp recorded by the speed sensor. Vehicle 2 is following immediately behind Vehicle 1, and Vehicle 3 is behind Vehicle 2, and so forth. The time column shows the time when vehicle passed the speed sensor. Speed and length are values recorded by the speed sensor. Vehicles are separated into either passenger cars (C) or trucks (T) based on their length. Those vehicles less than 25 feet in length are categorized as passenger cars, and those greater than 25 feet are identified as trucks.

In Table 4.10, speed difference is calculated as the difference in speed between a vehicle and the vehicle in front of it. For example, the speed difference for Vehicle 2 equals the speed of Vehicle 2 minus the speed of Vehicle 1. A positive value for speed difference indicates that the vehicle is travelling at a faster rate of speed than the vehicle in front of it. A negative value for speed difference indicates that the vehicle is travelling slower than the vehicle in front of it.

The time difference value shown in Table 4.10 equals the time between adjacent vehicles passing the sensor. The time difference for a vehicle is calculated as the difference in terms of time in which the vehicle passes the sensor compared to the vehicle immediately in front of it. For example, the time difference for Vehicle 2 is the time in which Vehicle 2 passed the sensor minus the time in which Vehicle 1 passed the sensor. All time difference values are positive.

The “distance from previous vehicle” column in the table shows how far a vehicle is behind the vehicle in front of it. It is calculated by multiplying the speed of the vehicle in front times the time difference. For example, the distance in which Vehicle 2 is from the vehicle in front of it (Vehicle 1) is calculated by multiplying the speed of Vehicle 1 times the time difference between Vehicles 1 and 2. The calculated distance apart is shown in both miles and feet.

Table 4.10: Sample of speed difference and distance calculations: 10 vehicles, 8:00pm, Day 5, with 35mph signs present

Vehicle No.	Time (hr:min:sec)	Speed (mph)	Length (feet)	Type of vehicle (Truck or Car)	Speed difference compared to previous vehicle (mph)	Time difference compared to previous vehicle (hours)	Distance from previous vehicle (miles)	Distance from previous vehicle (feet)
1	20:00:13	52	28	T	--	--	--	--
2	20:00:21	52	34	T	0	0.0022	0.1156	610
3	20:00:24	50	66	T	-2	0.0008	0.0433	229
4	20:00:29	53	65	T	3	0.0014	0.0694	367
5	20:01:08	36	71	T	-17	0.0108	0.5742	3032
6	20:01:14	38	73	T	2	0.0017	0.0600	317
7	20:01:17	42	16	C	4	0.0008	0.0317	167
8	20:01:25	46	20	C	4	0.0022	0.0933	493
9	20:01:28	40	59	T	-6	0.0008	0.0383	203
10	20:01:34	48	16	C	8	0.0017	0.0667	352

The speed difference, time difference, and distance apart values were calculated for all of the vehicles on all of the days of data collection. These values for the all of the vehicles recorded as part of the data collection are too extensive to show in this report. For this report, and for the analysis, Day 5 was chosen to represent days in which the 35mph advisory signs were implemented, and Day 7 was chosen to represent the condition without the 35mph signs. Only the data recorded by the 3rd work zone sensors was used in this analysis.

Figure 4.3 shows the speed differences for vehicles passing the 3rd work zone sensor from 8:00pm to 9:00pm on Day 5. This amounted to over 200 vehicles. The speed differences mostly range from -20mph to +20mph. No trend in the speed differences is apparent in the figure.

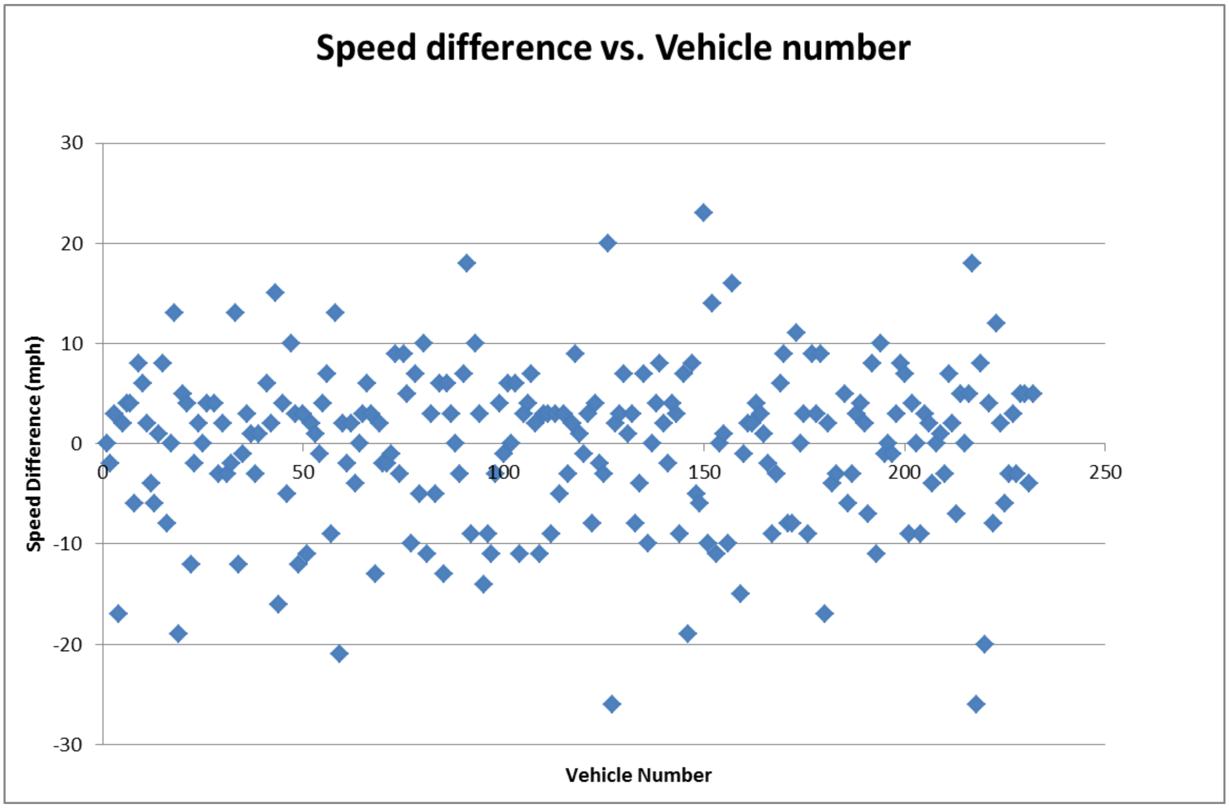

Figure 4.3: Speed difference for vehicles passing 3rd WZ sensor from 8:00-9:00pm of Day 5

Figure 4.4 shows the speed differences compared to the vehicle speed. The horizontal access contains the speed of the trailing vehicle, and the vertical axis contains the difference in speed between the trailing vehicle and the vehicle in front of it. The figure shows an apparent positive slope. That is, as the vehicle's speed increases, the difference in speed between the vehicle under consideration and the vehicle in front of it also increases. This trend is expected because the two factors are related in nature. Speed difference is calculated from vehicle speed. If the speed for the trailing vehicle is high, there is a greater chance that the speed difference will be high also.

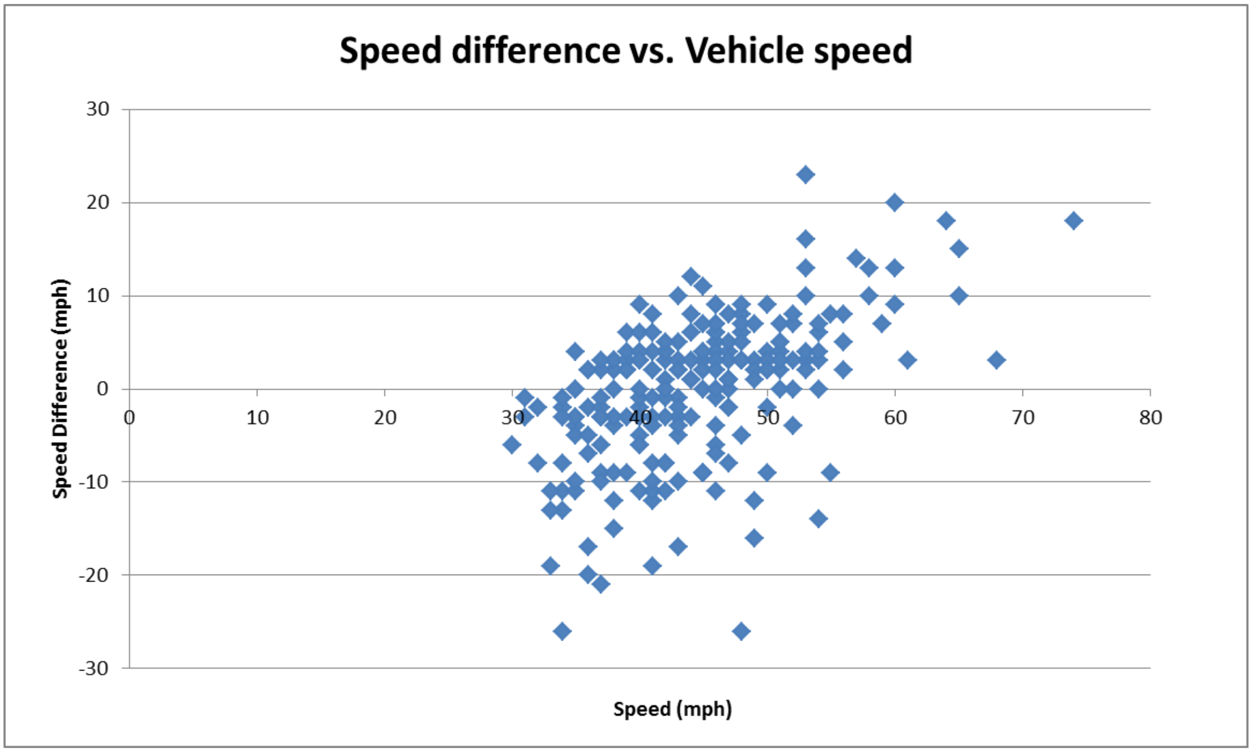

Figure 4.4: Speed difference vs. vehicle speed for vehicles passing 3rd WZ sensor from 8:00-9:00pm of Day 5

Figure 4.5 shows the distance between vehicles at different speeds. The majority of vehicles are approximately 1,000 feet (0.2 miles) apart or less. There is no clear trend between distance apart and the vehicle speed.

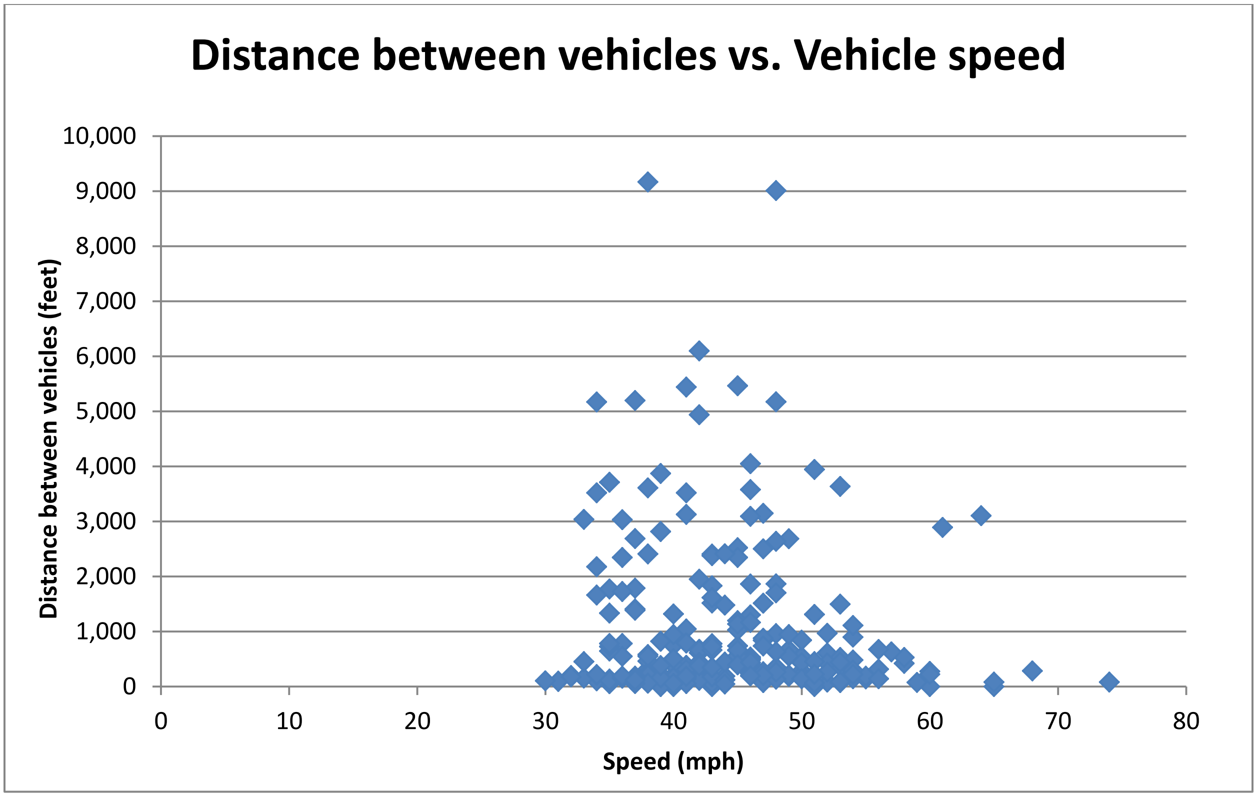

Figure 4.5: Distance between vehicles vs. vehicle speed for vehicles passing 3rd WZ sensor from 8:00-9:00pm of Day 5

Statistical tools were used to analyze the treatment effect of implementing the 35mph advisory signs. A two-sample t-test was conducted to see whether the 35mph signs have an effect on the speed difference. In the analysis, the absolute value of speed difference is used as the dependent variable. Absolute value is used due to the fact that, if the speed differences are added together, the negatives and positives will cancel each other and the mean of speed difference will be close to zero. The statistical test was conducted for all vehicles combined, for only passenger cars, and for only trucks. Table 4.11 summarizes the results. The data used to create the table consisted of all of the data recorded by the 3rd work zone sensor on Day 5 (with 35mph signs) and Day 7 (without 35mph signs) only.

Table 4.11: Effect of 35mph advisory signs on absolute value of speed differences between adjacent vehicles (Days 5 and 7, 3rd WZ sensor)

	Mean of absolute value of speed difference with 35mph signs present (mph)	**Mean of absolute value of speed difference without 35mph signs present (mph)**	**Difference in mean values (mph)**	**P-value**
All vehicles	7.08	7.53	0.45	0.13
Passenger cars	6.49	6.55	0.06	0.87
Trucks	7.59	8.35	0.76	0.09

For all vehicles, the 35mph advisory signs resulted in 0.45 mph higher speed difference, although the p-value is 0.13 which means this difference is not statistically significant. In other words, there is no statistically significant evidence that the mean of 7.08 mph with the 35mph signs present and the mean of 7.53 mph without the 35mph signs present are different. For passenger cars only, the p-value is 0.87 which indicates no difference in mean speeds when the 35mph signs are used compared to when the signs are not used. For trucks, the p-value is 0.09, which indicates potential difference, but not enough strength in the difference to be considered statistically significant. Overall, this test revealed that the 35mph signs have no impact on speed difference.

A second statistical analysis was performed using just the positive speed difference values. Positive speed difference represents a vehicle that is driving faster than the vehicle in front of it. This situation is possibly hazardous as it can lead to rear-end crashes. The results of the analysis are shown in Table 4.12. The results of this analysis are similar to the analysis using absolute value of speed differences. There is no statistical evidence that the 35mph advisory signs have an impact on speed difference between adjacent vehicles where the speed of the trailing vehicle is greater than the vehicle in front of it.

Table 4.12: Effect of 35mph advisory signs on vehicles with positive speed difference between adjacent vehicles (Days 5 and 7, 3rd WZ sensor)

	Mean of positive speed difference with 35mph signs present (mph)	**Mean of positive speed difference without 35mph signs present (mph)**	**Difference in mean values (mph)**	**P-value**
All vehicles	6.44	7.07	0.63	0.13
Passenger cars	5.52	5.86	0.34	0.48
Trucks	7.18	8.10	0.92	0.15

Similar to the analysis of speed values summarized in Figures 4.11 and 4.12, distance between adjacent vehicles is used as the dependent variable to assess the impact of the treatment (use of 35mph signs). Table 4.13 shows the results of the analysis. For all vehicles, there is moderate evidence that the 35mph signs have an impact on the distance between adjacent vehicles (p = 0.022). However, the separate analyses based on different types of vehicles (passenger cars and trucks) show there is no treatment effect on passenger cars and no effect on trucks (p = 0.18 and 0.09 respectively). There is enough difference in mean distance for cars and compared to that for trucks to lead to a statistically significant result when all vehicles are combined; yet when cars and truck are analyzed separately, there is less evidence that the treatment was the sole factor impacting the difference in mean distances for both types of vehicles.

Table 4.13: Effect of 35 mph advisory signs on distance between adjacent vehicles (Days 5 and 7, 3rd WZ sensor)

	Mean of distance apart with 35mph signs present (miles)	Mean of distance apart without 35mph signs present (miles)	Difference in mean values (miles)	P-value
All vehicles	0.301	0.342	0.041	0.022
Passenger cars	0.221	0.252	0.031	0.18
Trucks	0.372	0.416	0.034	0.09

As can be seen in the tables above, there is a difference in the mean values for passenger cars and the mean values for trucks. Therefore, additional statistical tests were conducted to explore the effect of vehicle type. Table 4.14 shows the results of these tests. Similar to the tables above, the values shown in the table are calculated from all of the data recorded by the 3rd work zone sensor on Days 5 and 7. The results suggest that vehicle type has an impact on speed difference and the distance between adjacent vehicles. Passenger cars have a lower speed difference and shorter distance to the vehicle in front of them. The p-values for both are very small, so the differences are statistically significant.

Table 4.14: Effect of vehicle type on speed difference and distance between adjacent vehicles (Days 5 and 7, 3rd WZ sensor)

	Passenger Cars	Trucks	Difference	P-value
Mean absolute value of speed difference (mph)	6.53	7.97	-1.44	1.282^{e-06}
Mean positive speed difference (mph)	5.69	7.62	-1.93	1.257^{e-06}
Mean distance between adjacent vehicles (miles)	0.237	0.394	-0.157	$< 2.2^{e-16}$

Based on the results shown in Table 4.14, when designing traffic control measures for work zones, passenger cars and trucks should be considered separately. Passenger car speed relative to the speed of the vehicle in front of the car is not as great as that for trucks, yet the distance apart is shorter. When designing traffic control plans, special consideration should be given to increasing the distance apart for passenger cars (e.g., minimize tailgating). Whereas for safety related to trucks, an emphasis should be placed on keeping the speeds of adjacent vehicles the same through the work zone.

5.0 CONCLUSIONS AND RECOMMENDATIONS

The results of the present study support and add to those of SPR-751 and SPR-769. Like the two previous studies, the results of the present study reveal that vehicle speed decreases as the vehicles approach the paver. Immediately downstream of the paver, vehicle speeds typically begin to increase. At the immediate vicinity of the paver, the speed is the lowest. For the I-5 Arlington to Tower Road project in the present study, the speeds reduced to approximately 35-38mph at the paver. The decrease to this speed took place over a distance of approximately 0.5 miles upstream of the paver. Similar to the previous studies, a conclusion can be made that this decrease in speed is likely due in part to the presence of the paver with its bright lights along with the extensive activity of all of the nearby workers and equipment. Drivers are more cautious and slow down in the presence of extensive equipment, lighting, workers, and activity. A decrease in vehicle speed at the paver occurred regardless of the difference in treatments (i.e., it occurred both with and without the 35mph signs). This is an important finding as it suggests that the traffic control treatments implemented may not affect the driving behavior of many drivers to a measurable extent. In addition, it suggests that a large amount of lighting (that does not create glare for the motorists and equipment operators), along with an active work area, are beneficial. The impact of the equipment on vehicle speed is also likely present at other similar pieces of equipment such as the paver.

In addition to slower speeds when passing the paver, vehicle speed varies throughout the length of the work zone. At the RWA sign location, vehicles travel at normal highway speeds. Passenger cars tend to travel faster than trucks. However, all vehicles begin to slow down at the 50mph regulatory signs. There is a gradual decrease in speed from the 50mph signs to the end of the taper. In the work zone, vehicles typically travel at a lower speed when they pass the paver and other equipment as described above. After passing the equipment the vehicles typically increase their speed to approximately 40-45mph over a distance of about 0.2 miles. This speed is then maintained through the rest of the active work area as the vehicles pass the other equipment. After passing the active work area, vehicle speed increases again to normal highway speed.

Several conclusions can be made specifically with regard to the 35mph advisory signs. Based on feedback from a variety of personnel involved in the preservation work, the signs are highly visible and easy to implement. The ease of implementation may vary depending on the roadway conditions (e.g., presence of a median and/or shoulder). Poor implementation may affect driver visibility of the signs.

Statistical analyses of vehicle speed comparing those days with the 35mph signs present to the days without the 35mph signs present reveal the following:

- The 35mph advisory signs impact vehicle speed. For all vehicles combined (both cars and trucks together), the mean speed with the 35mph signs present was 2.65mph lower than the mean speed without the 35mph signs present ($p\text{-value} < 2.2\ e^{-16}$).

- The 35mph advisory signs have a noticeable impact on passenger car speed, but less impact on truck speed. The mean speed for passenger cars with the 35mph signs is 4.17 mph lower than the mean speed without the 35mph signs present (p-value < 2.2 e^{-16}). For trucks, the difference is only 0.79 mph (p-value = 0.00059). Truck drivers may have a different interpretation of the meaning of advisory signs than passenger car drivers. The extent to which motorists understand the difference between regulatory and advisory speed signs can impact their reaction to the different types of signs.

- There is no statistically significant evidence that the difference in speed between adjacent vehicles is different with the 35mph signs present compared to when the 35mph signs are present. For all vehicles, the 35mph advisory signs resulted in 0.45 mph higher speed difference (absolute value of speed difference), although the p-value is 0.13 which means this difference is not statistically significant. Similar conclusions can be made when considering passenger cars and trucks separately. Therefore we cannot conclude that the difference in speeds were not due to chance or another confounding factor.

Additional analyses of the speed data lead to several conclusions that are not dependent on the presence of the 35mph advisory signs. These are:

- Prior to the work zone (at the RWA sign), passenger cars travel approximately 8 mph faster than trucks, and the speed variance for passenger cars is larger than the speed variance for trucks. A difference in speed and speed variance between passenger cars and trucks is also present at the 50mph regulatory signs and at the end of the taper. However, throughout the work zone, passenger cars travel approximately 2-3 mph slower than trucks and have about the same speed variance.

- Speed variance, for both passenger cars and trucks combined, is higher in the work zone than at the RWA signs and at the 50mph signs before the taper. This result may be due in part to the construction vehicles entering and exiting the work area. For example, construction vehicles slowing down to enter the work zone may occur when no other vehicles are present and therefore not impact the speed of other vehicles.

- Asphalt trucks have a large impact on traffic speed. Slow-moving asphalt trucks help to slow down the speeds of other vehicles. Including asphalt trucks in the TCP may be desired. For example, on one case study project in SPR-751, the contractor instructed the asphalt truck drivers to drive at no more than 45 mph in the work zone.

- Vehicle type has an impact on the difference in speed between adjacent vehicles. Adjacent trucks have a greater speed difference compared to adjacent passenger cars (p-value = 1.282^{e-06}).

- Vehicle type has an impact on the distance between adjacent vehicles. Adjacent trucks are typically farther apart in the work zone compared to adjacent passenger cars (p-value = 1.257^{e-06}).

The findings of the present study enable making recommendations for future practice. In addition to the recommendations provided in the SPR-751 and SPR-769 reports, the placement of 35mph signs periodically throughout the work zone is recommended to help decrease vehicle speeds and speed variability through the work zone. Based on the present case study, speeds for passenger cars and trucks will be less with the 35mph signs present (approximately 4.2 mph less for cars, and 0.8mph less for trucks). Multiple 35mph signs should be placed along the work zone, spaced at approximately 0.25 to 0.5 miles apart. The actual spacing should take into consideration the roadway features (e.g., curves, hills, and other signs present) to maximize sign visibility, minimize driver distraction, and take into consideration sign density. If the roadway conditions permit, the signs should be placed on both sides of the travel lane.

In this study, the 35mph advisory signs were used in conjunction with the 50mph regulatory signs. There was no indication from the speed data that using the 35mph advisory signs without the 50mph regulatory signs would cause concern. This comparison was not included as a research objective for the study. However, in light of previous research results recommending a two-step reduction in speed (see SPR-751 report), and possible driver confusion about the difference between a regulatory sign and an advisory sign, when 35mph advisory signs are used 50mph regulatory signs may also be warranted. Further study comparing the impacts of using the 35mph advisory signs with and without the 50mph regulatory signs would be needed.

With the addition of signs within the work zone, sign management is an important consideration as well. When permanent regulatory or advisory signs are present in the work zone that have different posted speeds than those on the temporary signs, the permanent signs need to be covered up or removed so as not to create driver confusion. In addition, temporary signs used during the course of the work should be removed or covered up between work shifts or between project phases. The presence of signs that do not apply to the current work zone conditions or vehicle speeds can confuse and frustrate drivers. If mis-managed, over time repeat drivers through the work zone may choose to ignore the signs, even those signs that are accurate and applicable to the conditions present. Prior to, during, and following each work shift, contractor and/or ODOT personnel should drive through the work zone to verify the accuracy of all of the signs present.

The results of this study are promising. A traffic control device that is easy to implement and can be implemented with minimal cost was found that helps slow down vehicle speeds. Further research evaluating motorist understanding of the difference between regulatory and advisory signs would be of interest. Placing more 35mph advisory signs throughout the work zone was a suggestion received in the interviews, and should be studied as well. Additional signs may remind motorist to maintain lower speeds more frequently throughout the work zone. The types of signs available for use should be investigated also. Sign stands that are more resistant to high winds may be more feasible and effective.

As described above, on Day 1 of the data collection, the contractor paved a very long distance (4 miles) and moved the taper location to the end of work zone during the last hour. The sensors were not relocated. Therefore, the speeds recorded at the end of taper location during that hour represent speeds when the taper was not present. The speeds recorded during this hour were approximately 5mph faster than the speeds recorded at the RWA location. The absence of a taper due to its relocation may have impacted this difference in speed. That is, after seeing the RWA signs, motorist tend to speed up if they do not see a taper or other traffic control device after driving a short distance downstream. Further research is recommended to determine the maximum distance between traffic control devices. If drivers do not see any devices after driving a given distance, they may speed up.

As mentioned in the SPR-769 report, in addition to studying the impact of traffic control devices on vehicle speed and speed variance, consideration of their impact on safety risk should also be included. For example, the speed reduction may be large due to one treatment, yet the safety risk associated with the treatment may increase also. The risk associated with each treatment would include additional factors such as: driver distraction and the safety of traffic control personnel while putting the treatment in place.

Additional research is also recommended to expose and test additional work zone traffic control devices that can be used to further improve motorist and worker safety. Examples of additional promising traffic control devices that would be worthwhile evaluating as part of future research studies are presented in the SPR-751 and SPR-769 reports.

6.0 REFERENCES

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