ACCELERATION LANE DESIGN FOR HIGHER TRUCK VOLUMES

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DISCLAIMER

ACCELERATION LANE DESIGN FOR HIGHER TRUCK VOLUMES

by

J. L. Gattis, Ph.D., P.E., Micah Bryant, and Lynette K. Duncan

CHAPTER 1

INTRODUCTION

Acceleration lanes allow drivers traveling at a lower speed while they are entering a roadway to increase their speed to one that is close to that of the main lanes before merging into the main lane traffic stream. The acceleration lane length design guidelines in the 2004 edition of the American Association of State Highway and Transportation Officials' (AASHTO) *A Policy on Geometric Design of Highways and Streets*, more commonly known as the Green Book, accommodate passenger cars, but the lengths are too short for large vehicles with poorer performance characteristics, such as tractor-trailer trucks (AASHO 1965).

The objective of this research project was to study the acceleration behavior of tractor-trailer trucks in actual operating conditions, and based on the observations evaluate the adequacy of current acceleration lane lengths and determine if longer lengths are needed to accommodate these larger trucks. The findings from this research are directed at locations with higher tractor-trailer truck volumes, such as at commercial vehicle weigh stations and freeway interchanges near truck stops or industrial facilities.

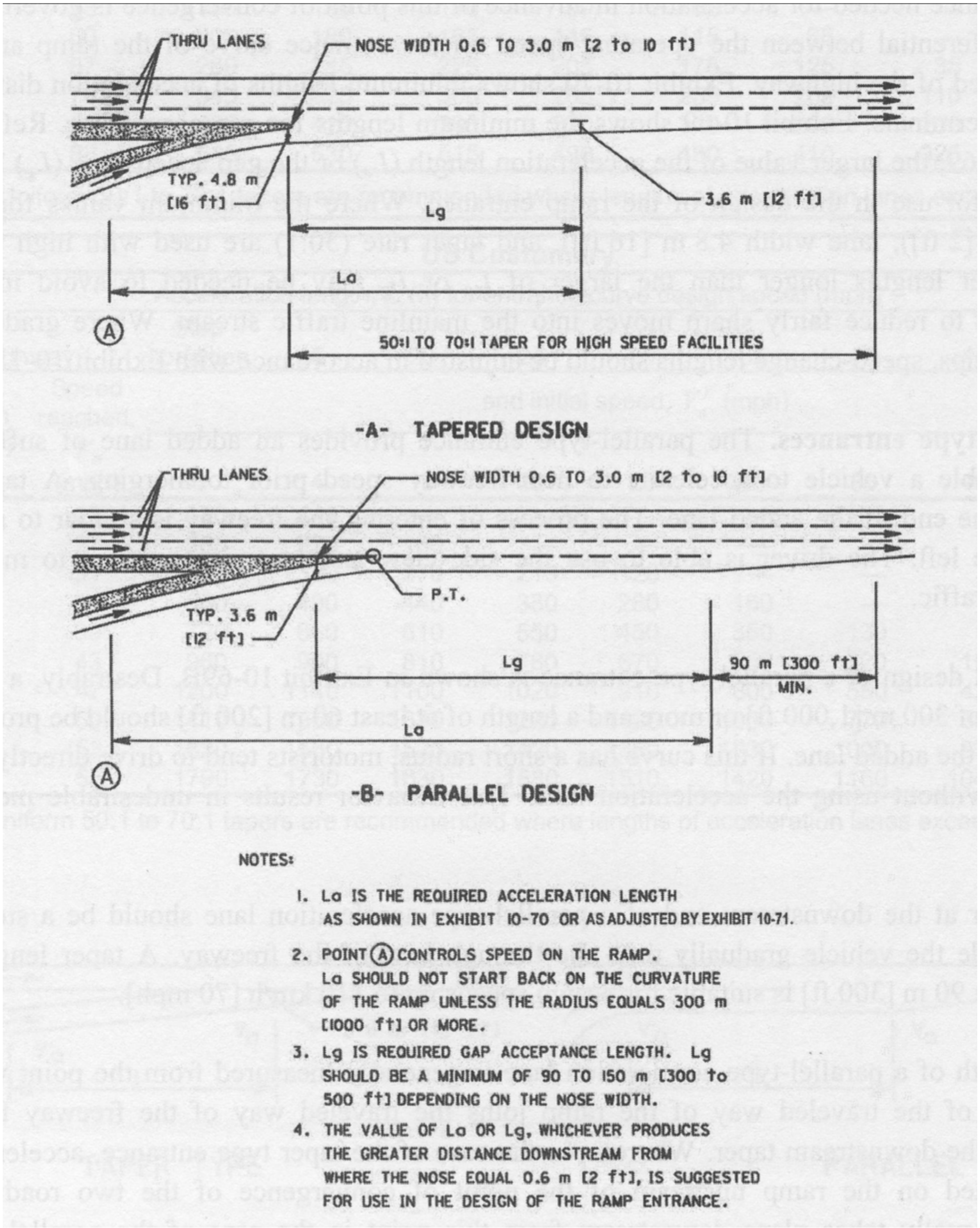
BACKGROUND

Acceleration lanes and deceleration lanes are both classified by the 2004 Green Book as speed-change lanes. They are used to increase the capacity, the efficiency, and the safety of the intersection of two roadways. The 2004 Green Book's reasoning behind the use of speed-change lanes, and directions regarding their length are:

> "Drivers leaving a highway at an interchange are required to reduce speed as they exit on a ramp. Drivers entering a highway from a turning roadway accelerate until the desired highway speed is reached. Because the change in speed is usually substantial, provision should be made for acceleration and deceleration to be

> accomplished on auxiliary lanes to minimize interference with through traffic and to reduce crash potential……A speed-change lane should have sufficient length to enable a driver to make the appropriate change in speed between the highway and the turning roadway in a safe and comfortable manner. Moreover, in the case of an acceleration lane, there should be additional length to permit adjustments in speeds of both through and entering vehicles so that the driver of the entering vehicle can position himself opposite a gap in the through-traffic stream and maneuver into it before reaching the end of the acceleration lane." (AASHTO 2004, p. 844)

The Green Book shows two types of geometric layouts for speed-change lanes, tapered and parallel. The difference between the two is that the tapered type facilitates a direct entry or exit at a flat angle from the roadway, and the parallel type consists of a full width travel lane running parallel to the roadway for some distance with a tapered section at the end. Figure 1-1 was reproduced from Exhibit 10-69 of the 2004 Green Book. The figure illustrates the different geometric configurations of the two types of speed-change lanes. Note that the tapered section at the end of the acceleration lanes is not included in the required acceleration lane length.



-A- TAPERED DESIGN

-B- PARALLEL DESIGN

NOTES:

1. La IS THE REQUIRED ACCELERATION LENGTH AS SHOWN IN EXHIBIT 10-70 OR AS ADJUSTED BY EXHIBIT 10-71.
2. POINT Ⓐ CONTROLS SPEED ON THE RAMP. La SHOULD NOT START BACK ON THE CURVATURE OF THE RAMP UNLESS THE RADIUS EQUALS 300 m [1000 ft] OR MORE.
3. Lg IS REQUIRED GAP ACCEPTANCE LENGTH. Lg SHOULD BE A MINIMUM OF 90 TO 150 m [300 to 500 ft] DEPENDING ON THE NOSE WIDTH.
4. THE VALUE OF La OR Lg, WHICHEVER PRODUCES THE GREATER DISTANCE DOWNSTREAM FROM WHERE THE NOSE EQUAL 0.6 m [2 ft], IS SUGGESTED FOR USE IN THE DESIGN OF THE RAMP ENTRANCE.

Figure 1-1: Acceleration Lane Types from 2004 Green Book

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CHAPTER 2

LITERATURE REVIEW

An initial task of this research project was to perform a review of several documents related to acceleration lanes and their design. The subjects examined included vehicle acceleration characteristics, acceleration lane design guidelines and their history, adjustment factors for current acceleration lane design guidelines, acceleration lane design for heavy commercial vehicles, design criteria for high speed roadways, the operation of large trucks, and vehicular collision factors. The relevant information found is summarized in this chapter.

DEEN’S STUDY OF HEAVY COMMERCIAL VEHICLES

In 1957, Deen wrote an article titled “Acceleration Lane Lengths for Heavy Commercial Vehicles”. He described a research project that studied the acceleration of heavy commercial vehicles in a real-world scenario, so that suggestions could be made regarding acceleration lane lengths required for these vehicles. The United States Congress had authorized the construction of thousands of miles of limited access highways, which could be entered only via acceleration lanes. The design guidelines of the time did not provide information about designing acceleration lane lengths for heavy commercial vehicles.

The study was conducted at the Lincoln Tunnel Interchange on the New Jersey Turnpike. At this location, all vehicles entering the roadway were required to stop at a toll booth, after which vehicles accelerated and entered the turnpike via an acceleration lane. There was a large bluff approximately forty feet high along side the acceleration lane and turnpike that provided locations for observing vehicles. The majority of the study site was on a level grade, however, the final 200 feet of the 1600 foot site were on a +0.4 percent grade. There was no roadside development or pedestrian interference at the site.

Whitewash lines were painted at measured distances from the toll booth. The lines extended from the edge of the traveled way onto the shoulder, and were painted every 100 feet for the first 600 feet, and then every 200 feet out to the end of the study site at 1600 feet. Three observers were placed on top of the bluff in positions so that all of the painted lines could be seen by at least one observer. The three observers used field telephones to communicate the instant at which selected vehicles crossed each line to a fourth observer who recorded the time of each instance using a twenty pen graphic recorder. Using the time data obtained from the recorder and the distances between data points, the researchers were able to determine the speed of the vehicles between each station. The vehicle accelerations were calculated from the changes in speed between the stations.

Initially the data set was divided into four categories of vehicles. There were 51 observations in the bus category, 59 observations in the single-unit truck category, 55 observations in the single trailer axle semi-trailer truck category, and 39 observations in the tandem trailer axle semi-trailer truck category. While there was no need to distinguish between loaded and unloaded vehicles because the desire of the study was to examine real-world behavior, obviously unloaded vehicles were not measured in an attempt to make the data as conservative as possible.

In the initial stages of the data analysis it was noted that semi-trailer trucks with single trailer axles and ones with tandem trailer axles had approximately the same acceleration characteristics. The two categories were not statistically significantly different, probably because of the small number of observations, so the data from the two categories were combined into a single semi-trailer truck category.

Time versus distance graphs showing mean and 85th percentile plots for each of the three vehicle categories were then constructed using the data set. The graphs clearly showed that semi-trailer trucks required more time to traverse the study area, and that the range of times for the semi-trailer trucks was greater than either of the two other categories. The graphs also showed that buses accelerated more uniformly than the other two categories, and that single-unit trucks traveled the study area distance faster than buses, but buses left the study area at a higher speed.

By determining the slope, which was the vehicle speed, of the mean data plots at five second intervals from the time versus distance graphs, the author was able to plot vehicle speed versus time for each of the three vehicle categories. The author performed the same process on the 85th percentile data plots, but cautioned that the resultant speed versus time plots, and any successive plots developed from them, did not represent the speeds that were less than 85 percent of the speeds at any instant. The speed versus time graph showed that the semi-trailer trucks were moving slower than the other categories at all points in time, and that the mean single-unit truck moved faster than the other two categories for the first twenty six seconds. After the first twenty six seconds, the mean bus moved faster than the other two categories.

By determining the slope, which was the vehicle acceleration, of the mean and 85th percentile plots at five second intervals on the speed versus time graph, the author was able to plot vehicle acceleration versus time for each of the three vehicle categories. From this graph it was noted that single-unit trucks has the smallest rate of acceleration after 21 seconds of travel, however, semi-trailer trucks actually traveled slower than single-unit trucks through the entire study distance.

The author constructed another graph showing the distance required for the mean and 85th percentile vehicles in each category to reach various speeds when starting from a stopped position. This graph showed that for the first 600 feet the mean single-unit truck traveled at a slightly higher speed than the mean bus, but the mean bus traveled faster from 600 feet onward. The graph also showed that all three categories of vehicles were still accelerating at the end of the study site, but the single-unit and semi-trailer truck categories showed signs of being asymptotic. This graph can be used to determine the length of acceleration lane needed for the classes of vehicles studied to accelerate from a stop to a given speed, and if assumed that the data are valid for vehicles accelerating from a speed other than zero, can be used more extensively by calculating the distance between two speeds.

Because the existing design standards at the time were developed using the mean normal acceleration rate of passenger cars, the author felt that the same approach should be used with the data collected in this project. The remaining discussions of the article only included the mean data from each vehicle category.

The required acceleration lane lengths that were calculated for the three vehicle categories were then compared to the values presented in the 1954 AASHO *Blue Book.* Three tables of proposed acceleration lane lengths were presented, one for each vehicle category. The tables presented for single-unit and semi-trailer trucks were developed under the assumption that the trucks would travel 5 mph less than the through traffic. The researchers found that the acceleration lane lengths provided in the 1954 *Blue Book* for design speeds at or below 50 mph were adequate for single-unit trucks, and that for design speeds of 60 mph and above the 1954 *Blue Book* lengths were inadequate for all heavy commercial vehicles. The author emphasized the need for additional study on vehicle performance on grades, acceleration rates at high speeds, and various locations. The table presented in this article for acceleration lane lengths for semi-trailer trucks has been reproduced in Table 2-1.

Table 2-1: Acceleration Lane Lengths for Semi-Trailer Trucks - Deen

design speed (mph)	pass. car running speed	assumed truck running speed	entrance curve design speed (mph)								
			stop	-	10	15	20	25	30	35	40
			assumed actual entrance speed (mph)								
			0	5	10	14	18	22	26	30	34
30	27	22	290	275	240	190	110				
40	34	29	700	685	650	600	520	410	210		
50	40	35	1240	1225	1190	1140	1160	950	750	460	100
60	45	40	1820	1805	1770	1720	1640	1530	1330	1040	680

AASHTO DESIGN GUIDELINES

Many state transportation agencies turn to the latest edition of the design guidelines published by the American Association of State Highway and Transportation Officials' (AASHTO) *A Policy on Geometric Design of Highways and Streets*, more commonly known as the Green Book. The 2004 Green Book discusses the role that large vehicles like tractor-trailer trucks play in the operation of roadways in several locations. While it does discuss the limitations of large vehicles and some of the design modifications that can be made to accommodate them, it does not require all aspects of a roadway to be designed around the characteristics of large vehicles. The majority of the information presented reflects passenger car operating characteristics.

Present Design Guidelines

When discussing the design of interchanges, the 2004 Green Book states that it is advantageous to place acceleration lanes on descending grades because it helps to shorten the acceleration distance needed by large vehicles. This is a desirable situation as long as the sight distance available to entering drivers is adequate enough for them to see gaps in the flow of traffic on the main lanes in time for them to maneuver into the gaps safely.

For acceleration lane length, the 2004 Green Book provides Exhibit 10-70. The exhibit includes a table that shows minimum acceleration lane lengths for various combinations of beginning and ending vehicle speeds. The exhibit also shows how the acceleration lane lengths are measured for both tapered and parallel geometric configurations. Green Book Exhibit 10-71 provides adjustment factors for the length of acceleration lanes that are on uphill or downhill grades of 3 to 6 percent. The acceleration lane length information from Exhibit 10-70 of the Green Book is reproduced in Table 2-2.

Table 2-2: Acceleration Lane Lengths from 2004 Green Book

		acceleration length (ft) for entrance curve design speed (mph)								
highway		stop condition	15	20	25	30	35	40	45	50
design speed (mph)	speed reached (mph)	and initial speed (mph)								
		0	14	18	22	26	30	36	40	44
30	23	180	140							
35	27	280	220	160						
40	31	360	300	270	210	120				
45	35	560	490	440	380	280	160			
50	39	720	660	610	550	450	350	130		
55	43	960	900	810	780	670	550	320	150	
60	47	1200	1140	1100	1020	910	800	550	420	180
65	50	1410	1350	1310	1220	1120	1000	770	600	370
70	53	1620	1560	1520	1420	1350	1230	1000	820	580
75	55	1790	1730	1630	1580	1510	1420	1160	1040	780

Evolution of the Design Guidelines

The 2004 Green Book does explain how the acceleration lane length values presented in Exhibit 10-70 were calculated, so previous versions of AASHTO highway design guidance were examined. The 2001, 1994, 1990, and 1984 versions of *A Policy on Geometric Design of Highways and Streets* did not state how the acceleration lane lengths were calculated. The 1973 *A Policy on Design of Urban Highways and Arterial Streets* referred to *A Policy on Geometric Design of Rural Highways,* the 1965 Blue Book. Since the acceleration lane length values in the 1965 Blue Book closely match the ones in the 2004 Green Book, it may be assumed that the source of the information is the same, and that minor changes have been made to the information over the course of several revisions.

The 1965 Blue Book did explain the procedure used to calculate the minimum acceleration lane lengths that it provided, and the criteria for the values used in the procedure. Three factors were used to calculate the minimum acceleration lane lengths: the speed at which drivers merge into through traffic, the speed at which drivers enter the acceleration lane, and the manner of accelerating or the acceleration factors. The assumptions made for two of these factors were that drivers would enter the acceleration lane at an average running speed that was determined from the design speed of the ramp's controlling curve, and that drivers would enter the flow of traffic in the main lanes at a speed that was equal to the main lane average running speed minus 5 mph. The acceleration rate values used in the calculations were derived from a plot of normal vehicle acceleration that was produced from the data of a 1937 Bureau of Public Roads study. The 1965 Blue Book contained Table VII-10 and Figure VII-18, which provided rounded and derived acceleration lane lengths.

NCHRP REPORT 505

National Cooperative Highway Research Program (NCHRP) Report 505, "Review of Truck Characteristics as Factors in Roadway Design" (2003), discussed the role of truck characteristics in roadway design. The objective of the research project was to ensure that the geometric design criteria presented in the 2001 AASHTO Green Book could reasonably accommodate the dimensions and performance characteristics of the trucks on the nation's roads at the time, and the anticipated characteristics of trucks in the future. The project only examined the geometric design issues; it did not examine structural or pavement issues related to trucks.

Truck-related geometric design issues addressed by the Green Book were examined, and the methodologies behind the recommendations made by the Green Book were evaluated. Two types of modifications were suggested by the authors of the report. The first was the use of different truck parameter values in the models used in the Green Book to determine design criteria for passenger cars. The second was to create revised models that would be more suitable for trucks. Design criteria in the Green Book that did not address trucks were also examined to determine if they should reflect truck characteristics.

An examination of truck weight limits and the current truck fleet composition found that all but four state governments in the 50 states plus the District of Columbia exercised the lowest maximum truck weight limit allowed by the Federal government of 80,000 pounds on the interstate system. Many states had higher maximum truck weight limits on roads other than interstates, and all of them had the right to issue permits for trucks that did not meet the weight requirements. It was also found that most combination trucks had weights of 60,000 pounds or more, based on 1997 Vehicle Inventory and Use Survey data. The same data indicated that approximately 3% of tractor-trailer trucks with single trailers and 11% of tractor-trailers with double trailers weighed above 80,000 pounds.

While discussing truck characteristics related to the geometric design of roadways, the authors describe the relationship between acceleration and truck weight-to-power ratio. They presented several sources that contained acceleration data that had been developed over the years by several studies. What they found was that the weight-to-power ratios of trucks had been decreasing for several years. They decided that a current sample of truck performance data should be taken so field studies were conducted as part of their research.

Nine different sites in three states were used in the field study. The sites were located on freeways and two-lane highways in California, Colorado, and Pennsylvania. The data from a study performed by Harwood in California in 1997 were also included in the analysis. What they found from the sample of current truck performance data was that the average truck weight-to-power ratios on freeways have stayed about the same in the eastern United States and have improved greatly in the western United States. The average weight-to-power ratios for tractor-trailer trucks were 141 pounds per horsepower in California, 115 pounds per horsepower in Colorado, and 168 pounds per horsepower in Pennsylvania.

The authors examined the guidance in the Green Book regarding critical length of grade and acceleration lanes. They found that the critical lengths of grade criteria set by the Green Book were based on three factors. The first factor was the weight and power of the representative truck used as the design vehicle. The second factor was the expected speed of the truck as it entered the critical length portion of the grade. The third factor was the minimum speed on the grade below which interference to following vehicles was considered unreasonable. Using these factors, the critical length of grade was set as the length of grade that would result in a 10 mph speed reduction for a 200 lb/hp truck. The design truck was chosen to be representative of the average truck in the United States. The Green Book gave two figures that were developed using the information presented for determining critical lengths of grade.

The authors felt that the guidance provided by the Green Book was insufficient for roadway design, so they proposed an alternate method for determining critical length of grade. The authors decided that truck performance prediction equations could be used to examine the relationship between truck speed profiles on specified grades and truck weight-to-power ratios. The truck performance equations from the TWOPAS computer simulation model were used to develop a spreadsheet known as the Truck Speed Performance Model (TSPM). The TSPM used a truck weight-to-power ratio, a roadway profile, and an initial truck speed at the foot of the grade to construct a speed versus distance profile for the specified situation. The authors felt that the TSPM provided a much more versatile tool for designers to use because it incorporated site-specific conditions.

The authors then examined the guidance surrounding acceleration lane design presented in the Green Book. This guidance consisted of two tables, one that provided minimum acceleration lane lengths, and one that provided adjustment factors that were to be used on the minimum acceleration lane lengths when the lanes were located on grades. Using the TSPM, the authors determined the weight-to-power ratios implied by the Green Book acceleration lane length values. Because the minimum acceleration lane length table in the Green Book was intended for roadway grades of 2% or less, the authors conducted analyses for both 0% and 2% grades.

The analyses on the minimum acceleration lane lengths presented in the Green Book indicated that trucks with weight-to-power ratios ranging from 100 to 145 lb/hp could sufficiently accelerate to the given speeds within the minimum acceleration lane lengths, on a 0% grade. For a 2% grade, trucks with weight-to-power ratios ranging from 65 to 110 lb/hp were required to accelerate to the given speeds within the minimum acceleration lane lengths. Because the design vehicle used by the Green Book had a weight-to-power ratio of 200 lb/hp and the range of 85th percentile weight-to-power ratios found in the field study conducted by the authors was between 170 and 210 lb/hp, the authors concluded that the design guidance provided by the Green Book would accommodate an average truck but not a heavily loaded one.

The TSPM was then used to determine the minimum acceleration lane lengths required for a 180 lb/hp truck to accelerate based on the conditions used in the Green Book table and a 0% grade. These values are reproduced in Table 2-3. The minimum acceleration lane lengths calculated using the TSPM were on average about 1.8 times greater than the minimum acceleration lane lengths provided in the Green Book.

Table 2-3: Acceleration Lane Lengths Calculated in NCHRP Report 505 using the TSPM for a 180 lb/hp Truck on a 0% Grade

		acceleration length (ft) for entrance curve design speed (mph)								
highway		stop condition	15	20	25	30	35	40	45	50
design speed (mph)	speed reached (mph)	and initial speed (mph)								
		0	14	18	22	26	30	36	40	44
30	23	275	160							
35	27	400	300	230						
40	31	590	475	400	310	170				
45	35	800	700	630	540	400	240			
50	39	1100	1020	950	850	720	560	200		
55	43	1510	1400	1330	1230	1100	920	580	240	
60	47	2000	1900	1830	1740	1600	1430	1070	760	330
65	50	2490	2380	2280	2230	2090	1920	1560	1220	800
70	53	3060	2960	2900	2800	2670	2510	2140	1810	1260
75	55	3520	3430	3360	3260	3130	2960	2590	2290	1850

TEXAS TRANSPORTATIUON INSTITUTE STUDIES

Two papers submitted for the 2007 Transportation Research Board (TRB) annual meeting examined acceleration lane length design guidance found in the 2004 AASHTO Green Book.

Study of Acceleration Lane Lengths

In “Potential Updates to the 2004 Green Book Acceleration Lengths for Entrance Terminals”, Fitzpatrick and Zimmerman examined 2004 Green Book Exhibit 10-70, which includes a table used for determining acceleration lane length, and attempted to trace the history of the information in this table in order to gain an understanding of the design methodology. Once the design methodology was understood, the authors extended the acceleration lane length values to accommodate design speeds greater than 80 mph, and then examined other methods of calculating acceleration lane lengths.

The first step that the authors took towards extending the current 2004 Green Book acceleration lane lengths to higher design speeds was to examine the design methodology used to calculate the acceleration lane lengths found in the table. The 2004 Green Book does not state how the values were calculated, and so the authors began examining previous versions of AASHTO roadway design guides. They found that in the 1965 AASHO publication *A Policy on Geometric Design of Rural Highways*, more commonly known as the 1965 Blue Book, that the acceleration lane lengths were either the same as or very close to the ones in the 2004 Green Book. The major differences in the information given in the two sources were that the 1965 Blue Book included the length of the taper as part of the acceleration lane while the 2004 Green Book listed the taper lengths separately, there were slight differences between acceleration lane length values for certain speed combinations, and the 2004 Green Book includes values for 5 mph speed increments while the 1965 Blue Book only has values for speed increments of 10 mph (Fitzpatrick and Zimmerman 2006).

The 1965 Blue Book did contain information regarding the source of the acceleration lane length values found in the table. According to the authors, the 1965 Blue Book states that the length of an acceleration lane is based on the speed at which drivers enter the acceleration lane, the acceleration factors, and the speed at which drivers merge into the through traffic. The assumptions for these factors used in the development of the 1965 Blue Book table were that drivers would exit the controlling curve on the ramp at an average running speed that was lower than the design speed of the curve, the acceleration rates for vehicles would be the same as normal acceleration rates for vehicles as determined in a 1937 Bureau of Public Roads study, and the speed of the entering vehicles would be 5 mph less than the average running speed of the through roadway (Fitzpatrick and Zimmerman 2006). The authors argued that these assumptions were out of date and need to be updated using findings from more recent research.

Using the assumptions stated above and the uniform acceleration formula, the authors were able to reproduce the acceleration lane length values found in both the 1965 Blue Book and the 2004 Green Book by changing the acceleration rate values. Once this was completed, the authors examined the acceleration rates and found that the trend was a decrease in acceleration rate as initial vehicle speed increased.

Since the authors felt that the assumptions used in the development of the 1965 Blue Book acceleration lane lengths were not supported by recent research, they examined the effect of using the design speed of the roadway instead of the average running speed in order to propose possible acceleration lane lengths. They found that using the design speed rather than the running speed resulted in acceleration lane lengths that were much larger. They suggested that the use of acceleration values that are more representative of modern vehicles could help to offset some of the difference (Fitzpatrick and Zimmerman 2006).

Next, the authors examined another method of calculating acceleration distance. Vehicle performance equations that predict moment-to-moment vehicle acceleration values were obtained from National Cooperative Highway Research Project (NCHRP) Report 505 and Texas Department of Transportation (TxDOT) project 5544. Both studies produced spreadsheets which were used to predict acceleration lengths based on various vehicle characteristics. Characteristics for the 1986 and 2004 passenger car and light truck vehicle fleet were obtained from the National Highway Traffic Safety Administration and used by the authors in both spreadsheets.

The authors found that the NCHRP spreadsheet produced acceleration lane lengths that were much larger than the ones found in the 2004 Green Book. They stated that this was because the spreadsheet was developed to produce acceleration lengths for large trucks; it included gear shift delay and other attributes that did not apply to the operation of passenger cars and light trucks. The TxDOT spreadsheet resulted in acceleration lengths that were significantly shorter than the ones found in the 2004 Green Book. The authors caution that the acceleration rates used in these calculations represent optimal acceleration rates, not ones typically chosen by drivers, and that modification of these rates could produce better results (Fitzpatrick and Zimmerman 2006).

Constant acceleration rates were also examined by the authors because they provide an easy method of calculating an approximate acceleration length. Maximum acceleration rates were obtained from the Institute of Transportation Engineers' (ITE) *Traffic Engineering Handbook*, and average acceleration rates were obtained from the 2004 Green Book, a TxDOT study, and a Canadian study. These acceleration rates were then used to calculate acceleration distances, and the values were compared to the ones in the 2004 Green Book.

The authors found that the maximum acceleration rates obtained from ITE produced acceleration distances shorter than the ones in the 2004 Green Book, and that the average acceleration rates produced acceleration distances that were near or exceeded the lengths found in the 2004 Green Book.

The recommendation made by the authors included using the average constant acceleration rate of 2.5 ft/s^2 as determined in a Canadian study, the highway design speed, and the ramp curve design speed to calculate potential acceleration distances (Fitzpatrick and Zimmerman 2006). This procedure will result in acceleration lane lengths greater than the ones given in the 2004

Green Book. The table of potential acceleration lane lengths, in feet, that the authors proposed has been reproduced in Table 2-4.

Table 2-4: Acceleration Lane Lengths from Fitzpatrick and Zimmerman

highway design speed (mph)	acceleration length for entrance curve design speed (mph) stop condition	15	20	25	30	35	40	45	50
30	389	292	216						
35	529	432	357	259					
40	691	594	519	421	303				
45	875	778	702	605	486	346			
50	1080	983	908	810	691	551	389		
55	1307	1210	1134	1037	918	778	616	432	
60	1556	1459	1383	1286	1167	1026	864	681	475
65	1826	1729	1653	1556	1437	1297	1134	951	746
70	2118	2020	1945	1848	1729	1588	1426	1243	1037
75	2431	2334	2258	2161	2042	1902	1740	1556	1351

The authors conclude the paper with the following list of topics that they feel could benefit from additional research:

- The appropriate speed to assume for merging vehicles.
- The vehicle's speed when exiting the controlling ramp curve.
- Examination of vehicle acceleration rates, constant or varied.
- Is a constant acceleration appropriate?
- Will trends in vehicle performance continue as they have been?
- Should the acceleration based model be replaced by a gap acceptance model?
- Should the model be a function of the grade that the ramp is on?
- What are the tradeoffs of using increased acceleration lane lengths and how does safety compare?

Study of Acceleration Lane Length Grade Adjustment Factors

In "Potential Changes to the 2004 Green Book Adjustment Factors for Entrance and Exit Terminals", Fitzpatrick and Zimmerman discussed the design guidance surrounding the adjustment factors for acceleration and deceleration lane length provided by the 2004 AASHTO Green Book. The authors examined Green Book Exhibit 10-71, which gives factors to adjust the length of acceleration and deceleration lanes that are located on grades.

The authors examined the speed-change lane adjustment factors presented by the 2004 Green Book and extrapolated the range of values in the table out to design speeds of 80 mph. They found that the extrapolated values appeared unreasonable. They decided to examine the design methodology used to calculate the 2004 Green Book values, and to develop a better procedure which would include values for higher speed roads.

The 2004 Green Book did not discuss the design methodology used, so the authors examined previous editions of AASHTO highway design guidance. They found that the 1954 *Policies on Geometric Highway Design*, which is known as the 1954 Blue Book, contained speed-change lane adjustment factors that were similar to the ones in the 2004 Green Book. While the values were consistent between the two sources, the 1954 Blue Book only provided values for 10 mph increments of design speed while the 2004 Green Book provided values for 5 mph increments of design speed. The additional values in the 2004 Green Book appeared to be the average of the adjoining values in the 1954 Blue Book. Because of the similarities, the authors concluded that the source of the information was probably the same.

According to the authors, the 1954 Blue Book stated that the speed-change lane adjustment factors were developed by using engineering judgment to apply principles of mechanics to rates of speed change for level grades. The 1954 Blue Book's reason for using engineering judgment was that data on driver behavior during acceleration or deceleration on grades was not available.

In order to develop potential adjustment factors for acceleration lanes, the authors decided to use vehicle performance prediction equations to calculate the distance required for a vehicle to accelerate from various beginning speeds to various ending speeds on a level grade and on various uphill and downhill grades. The ratio of the distance traveled on grade to the distance traveled on level grade would then be the adjustment factor for the set of speeds in question.

The authors used two sources of vehicle performance prediction equations. The first was TxDOT spreadsheet 5544. The authors developed this spreadsheet to predict vehicle speeds based on several variables related to vehicle performance and roadway grade. It was created using several references that contained equations for generating vehicle speed profiles. The second source was a spreadsheet that was developed as part of NCHRP Report 505. The report was on truck characteristics in highway design, and the spreadsheet predicted truck speeds on various grades. The NCHRP spreadsheet was designed specifically for trucks and included factors that do not greatly influence passenger car behavior such as gear shift delay.

Both spreadsheets were used to create speed profiles for vehicles on various grades using vehicle characteristic data from the 1986 and 2004 passenger car and light truck fleet. These results were then compared to maximum vehicle performance data for several late model passenger cars that included some high performance vehicles. The 1986 and 2004 fleet data were obtained from the National Highway Traffic Safety Administration. The late model passenger car data were obtained from *Car and Driver* magazine, and the high performance vehicle data were obtained from the internet.

In general, the predictions made by the TxDOT spreadsheet matched the late model passenger car data. However, even though the pattern of results from the TxDOT spreadsheet appeared reasonable, they represented optimum vehicular performance, not the acceleration behavior generally used by drivers. Acceleration attributes based on the 1986 and 2004 passenger car and light truck fleet data were closer to what might be actually found, but still on the upper end of the actual range. The authors suggested using acceleration data from in-field measurements in the spreadsheet to obtain more accurate results.

The NCHRP spreadsheet produced acceleration lengths that were much larger than the ones found in the 2004 Green Book, and would not exceed a speed of 79 mph regardless of what speed was desired. The authors concluded that since the spreadsheet was developed for trucks, changes must be made to the equations in order to correctly predict passenger car performance even if passenger car vehicle characteristics are entered.

To develop the final proposed speed-change lane length adjustment factors, the authors used the results of the TxDOT spreadsheet that were obtained using the 2004 passenger car and light truck fleet data. They calculated the ratios of acceleration distance on grade to acceleration distance on level grade for speeds ranging from 20 mph to 80 mph and grades ranging from -6 percent to +6 percent. They found that for speeds less than 50 mph, the ratio was almost 1.0 for each combination of starting and ending speeds, and for speeds above 60 mph it varied depending upon the final speed and grade. While there were some variations between the TxDOT spreadsheet factors and the ones found in the 2004 Green Book, the overall trends were the same. Using the TxDOT spreadsheet results and some engineering judgment, the authors compiled a table of suggested speed-change lane adjustment factors that ranged from 0.8 on a -6 percent grade to 1.4 on a +6 percent grade for an 80 mph design speed.

The authors conclude the paper with comments on the need for in-field vehicle performance measurement, and propose that the following things should be addressed:

- Do the suggested values reflect the capabilities of current vehicles?
- How should the types of vehicles present on a ramp affect the adjustment for grade?
- How could the adjustment factors be a function of percent heavy vehicles?
- Exploration of the tradeoffs for using the suggested adjustment factors.

MICHIGAN STUDY

Researchers at the University of Michigan Transportation Research Institute (UMTRI) examined the effects that the geometric design of freeway interchanges had on tractor-trailer truck accidents. They examined multiple sources of vehicular accident information in order to identify several freeway interchange ramps that were problematic for tractor-trailer trucks. Once these locations had been identified, they constructed several computer simulation models that examined the dynamic responses of various tractor-trailer trucks due to the effects of some specific geometric features of the interchange ramps.

The purpose of the study was to examine truck operating characteristics as they related to the current AASHTO Green Book design criteria for highways. The authors argued that the current design guidance was based on passenger car operation and did not take the operating characteristics of tractor-trailer trucks into account. This they said created a safety hazard because tractor-trailer trucks operating under normal design speed conditions for a passenger car had little or no margin of safety from accidents in areas such as deceleration lanes and entrance and exit ramps at interchanges.

In their review of previous studies, the authors reference a conclusion from a 1969 Bureau of Public Roads study. This conclusion stated that the congestion caused by commercial vehicles in traffic was judged to contribute to vehicular accident probability (Ervin et al. 1985).

After performing the computer simulations on truck behavior, the authors believed that in order to compensate for trailer-truck operating characteristics, interchange designs based on truck rollover theory should be used instead of the truck skidding theory currently used. This is important to the design of acceleration lanes because the controlling ramp curve immediately preceding parallel type acceleration lanes is one of the locations where the authors state that tractor-trailer trucks have a narrow safety margin, therefore, rollover design methodology should be used.

The authors noted that tractor-trailer trucks need a much larger distance to accelerate to freeway speeds than do passenger cars. They stated “it is useful to note that the severe limitation in this performance area very likely influence the driving strategy of truck drivers in certain respects”. They felt that it was reasonable to expect that because of the lack of acceleration capability, drivers tended to avoid reductions in speed whenever possible. Because of the large speed differential between tractor-trailer trucks and passenger cars at acceleration lanes, the authors felt that the situation caused tractor-trailer truck drivers to maneuver through the ramp curves at dangerous speeds to help them merge into the freeway. The design of the acceleration lane thus became an indirect cause of certain accidents on interchange ramps such as rollovers, jackknifes, and off-road loss of control maneuvers.

CHAPTER 3

DATA COLLECTION

This research examined acceleration behaviors of tractor-trailer trucks as they exited weigh stations and via an acceleration lane entered traffic on a freeway. The data needed to describe the acceleration behavior of tractor-trailer trucks consisted of measurements of speed, distance, and time for individual vehicles at several locations throughout the acceleration event. The weights of the trucks and the volumes of vehicles on the main lanes of the freeway were also recorded so that the collected data could be segregated into groups based on weight and volume.

Before data could be collected, suitable sites for collecting the data, and a plan for obtaining the needed data had to be developed.

SITE SELECTION

To the extent possible, it was desirable that the selected sites have similar characteristics such as physical layout and acceleration lane type so that comparisons and contrasts could be made among data from the sites. The sites also needed to have different characteristics like various acceleration lane and roadway grades so that differences in the data between sites could be examined. One other major consideration was the locations of the selected weigh stations. The time and money available for the data collection portion of this research project made the selection of the weigh station locations important because it was desired to collect the maximum amount of data possible.

The process began with the identification of weigh stations in Arkansas, Missouri, Oklahoma, Tennessee, and Mississippi. Some weigh stations were located by finding their address and phone number on a website. These websites were generally operated by either the state’s department of transportation or the highway police. Others were located by calling the state department of transportation or highway police, asking for the weigh station location, and explaining the research project that was going to be conducted. Appendix A lists the sites identified as initial candidates for data collection.

Once the locations of the weigh stations had been determined, more information about each location was sought. The weigh stations were visually identified and tagged on aerial photographs using the computer program Google Earth. The route on which each weigh station was located was determined and recorded during the process of locating the weigh station sites. The log miles for all of the weigh station sites in Arkansas were located using county route and section maps obtained from the Arkansas Highway and Transportation Department (AHTD). The log miles for six of the weigh station sites in Oklahoma were contained in an email sent by an employee of the Oklahoma Department of Transportation (ODOT). The log miles for six of the weigh station sites in Missouri were obtained by calling the Missouri Department of Transportation (MoDOT). The log miles for two of the weigh station sites in Tennessee were obtained through an in-person inspection of the sites. The average daily traffic (ADT) for the section of freeway in which the weigh stations were located was obtained for each weigh station using ADT maps found on the internet at the various DOT websites.

The third step in selecting suitable data collection sites involved the elimination of some sites and the collection of additional information about the suitability of other sites. The criteria that were used to eliminate weigh stations from the list of possible data collection sites included problems with the physical layout of the weigh station and the location of the weigh station. Information about the lack of acceleration lanes at two of the weigh stations and very short acceleration lanes at two other weigh stations in Oklahoma was obtained via email, and these sites were therefore deemed unsuitable. The weigh stations in eastern Tennessee, northern Missouri, and western Oklahoma were deemed less desirable because of their distance from Fayetteville, Arkansas.

In-person inspections of twelve weigh station sites in Arkansas and two in Missouri were made. During these inspections, notes about the physical layout, grade, operation, and potential obstacles to data collection were recorded. Photographs were also taken of most of the sites during the inspections for easy reference to the site’s characteristics at a later date.

The next step in selecting suitable data collection sites was to evaluate and compare the physical characteristics of the weigh station sites in Arkansas and two near Joplin, Missouri, and select sites where data collection would be possible and produce the desired quality of data. The criteria used to determine if a site’s layout was suitable included a fairly straight horizontal alignment, and a vertical alignment with a constant grade or few variations. These criteria were used so that attributes that were constant or nearly constant between the sites could be linked. Other criteria such as having no obstructions within the data collection area and adequate areas to place the data collection equipment were examined because these factors would affect the ability of the research team to collect data.

SELECTED DATA COLLECTION SITES

The suitable weigh station sites that were selected for data collection were located near Alma, Hope, Joplin, Lehi, and Marion. All of these sites had tractor-trailer truck volumes that were determined to be adequate for data collection. At all of the sites, the weigh stations are oriented parallel to the freeway, and there is a depressed grass outer separation between the freeway and the weigh station. All of the sites have reverse curves connected to acceleration lanes that lead out of the weigh station and back onto the freeway. The deceleration and/or acceleration lanes at all of the sites are designed parallel to the freeway and either begin or end with a tapered section.

Alma Eastbound Weigh Station

The weigh station near Alma, Arkansas is located on Interstate 40 in section 11 at log mile 9. There are weigh stations for both the eastbound and westbound traffic, but only the weigh station for the eastbound traffic was selected for data collection. The westbound weigh station at this location was located too close to the succeeding exit ramp.

The traffic lane that enters the weigh station is on a slight uphill grade, and has undulations to facilitate drainage. Trucks encounter a set of weigh-in-motion plates just after exiting the freeway. The traffic lane then splits into two lanes. The lane on the left is used by trucks that are cleared to pass through the weigh station without stopping. They are cleared based on their weight reading from the weigh-in-motion plate system. The lane on the right leads to the static truck weight scales directly in front of the weigh station building. The static scales are used to weigh trucks more accurately. Figure 3-1 shows the static scales and the weigh station building at the Alma weigh station. The weigh station is separated from the freeway by a narrow depressed grass outer separation. The traffic lanes that pass through the weigh station are on a slight uphill grade. After passing the weigh station building the two lanes merge back into one, and then enter the reverse curve which leads to the freeway acceleration lane. The acceleration lane and freeway after it at this site are on an increasing uphill grade. Figure 3-2 shows the freeway acceleration lane at the Alma weigh station.

Figure 3-1: Alma Weigh Station Building and Static Scales

Figure 3-2: Alma Weigh Station Freeway Acceleration Lane

Hope Eastbound Weigh Station

The weigh station near Hope, Arkansas is located on Interstate 30 in section 12 at log mile 26. There are weigh stations for both the eastbound and westbound traffic, but only the weigh station for the eastbound traffic was selected for data collection.

The traffic lane that enters the weigh station is on a level grade. Trucks encounter a set of weigh-in-motion plates after exiting the freeway. The traffic lane then splits into two lanes. The lane on the left is used by trucks that are cleared to pass through the weigh station without stopping. They are cleared based on their weight reading from the weigh-in-motion plate system. The lane on the right leads to the static truck weight scales directly in front of the weigh station building. The static scales are used to weigh trucks more accurately. Figure 3-3 shows the static scales and the weigh station building at the Hope weigh station. The weigh station is separated from the freeway by a wide depressed grass outer separation that is filled with trees. The traffic lanes that pass through the weigh station are on a level grade that becomes slightly downhill after the static scales. After passing the weigh station building the two lanes merge back into one, and then enter the reverse curve which leads to the freeway acceleration lane. The acceleration lane and freeway after it at this site are on an increasing downhill grade. Figure 3-4 shows the freeway acceleration lane at the Hope weigh station.

Figure 3-3: Hope Weigh Station Building and Static Scales

Figure 3-4: Hope Weigh Station Freeway Acceleration Lane

Joplin Westbound Weigh Station

The weigh station near Joplin, Missouri is located on Interstate 44 at both county and continuous primary direction (east) log mile 3. There are weigh stations for both the eastbound and westbound traffic, but only the weigh station for the westbound traffic was selected for data collection. This weigh station was the only site at which data were collected that did not have a weigh-in-motion system.

The weigh station is separated from the freeway by a narrow depressed grass outer separation. The traffic lane that enters the weigh station after the deceleration lane is on a slight downhill grade. The traffic lane then splits into two lanes. The left lane is used to bypass trucks through the weigh station. This lane is only used when the number of trucks waiting to use the static scales causes a backup onto the freeway. The right lane leads to the static truck weight scales directly in front of the weigh station building. Figure 3-5 shows the static scales and the weigh station building at the Joplin weigh station. After passing the weigh station building the two lanes merge back into one, and then enter a reverse curve which leads to the freeway acceleration lane. The traffic lanes that pass through the weigh station are on a slight downhill grade which turns slightly uphill just before the acceleration lane. The acceleration lane and freeway after it at this site are on a slight downhill grade. Figure 3-6 shows the freeway acceleration lane at the Joplin weigh station.

Lehi Eastbound Weigh Station

The weigh station near Lehi, Arkansas is located on Interstate 40 in section 52 at log mile 273. The only operational weigh station at this location is the one for eastbound traffic. The westbound weigh station was closed and replaced by a new weigh station in another location.

The traffic lane that enters the weigh station is on a level grade. Trucks encounter a set of weigh-in-motion plates just after exiting the freeway via a deceleration lane. The traffic lane then splits into two lanes. The lane on the left is used by trucks that are cleared to pass through the weigh station without stopping. They are cleared based on their weight reading from the weigh-in-motion plate system. The lane on the right leads to the static truck weight scales directly in front of the weigh station building. The static scales are used to weigh trucks more accurately. Figure 3-7 shows the static scales and the weigh station building at the Lehi weigh

Figure 3-5: Joplin Weigh Station Building and Static Scales

Figure 3-6: Joplin Weigh Station Freeway Acceleration Lane

station. The weigh station is separated from the freeway by a narrow depressed grass outer separation. The traffic lanes that pass through the weigh station are on a level grade. After passing the weigh station building the two lanes merge back into one, and then enter the reverse curve which leads to the freeway acceleration lane. The acceleration lane and freeway after it at this site are on a slight uphill grade that eventually levels off and then becomes slightly downhill. Figure 3-8 shows the freeway acceleration lane at the Lehi weigh station.

Marion Southbound Weigh Station

The weigh station near Marion, Arkansas is located on Interstate 55 in section 11 at log mile 9. The only operational weigh station at this location is the one for southbound traffic. The northbound weigh station is closed because its function is now being served by a new weigh station in another location.

The traffic lane that enters the weigh station is on a slight uphill grade. Trucks encounter a set of weigh-in-motion plates just after exiting the freeway via a deceleration lane. The traffic lane then splits into two lanes. The lane on the left is used by trucks that are cleared to pass through the weigh station without stopping. They are cleared based on their weight reading from the weigh-in-motion plate system. The lane on the right leads to the static truck weight scales directly in front of the weigh station building. The static scales are used to weigh trucks more accurately. Figure 3-9 shows the static scales and the weigh station building at the Marion weigh station. The weigh station is separated from the freeway by a narrow depressed grass outer separation. The traffic lanes that pass through the weigh station are on a level grade. After passing the weigh station building the two lanes merge back into one, and then enter the reverse curve which leads to the freeway acceleration lane. The grade of the lane through reverse curve is slightly uphill, and then changes to slightly downhill just before acceleration lane. The acceleration lane and freeway after it at this site are on a slight uphill grade that eventually leads to a much steeper uphill grade at a grade separated roadway crossing. Figure 3-10 shows the freeway acceleration lane at the Marion weigh station.

Figure 3-7: Lehi Weigh Station Building and Static Scales

Figure 3-8: Lehi Weigh Station Freeway Acceleration Lane

Figure 3-9: Marion Weigh Station Building and Static Scales

Figure 3-10: Marion Weigh Station Freeway Acceleration Lane

Table 3-1 and Figure 3-11 show a tabular and graphical representation of the characteristics of the data collection sites. The location, traffic direction, grades, and distances to the acceleration lane gore points and taper points are given for each site.

Table 3-1: Data Collection Weigh Station Site Information

Site	Direction of Travel	Route, Log Mile	Composite Grade from 0' to 2000'	Distance from end-of-scale to gore point	to begin taper	to end taper
Alma	Eastbound	I-40, 9	+0.8%	1100'	1750'	2050'
Hope	Eastbound	I-30, 26	-0.6%	1400'	2000'	2200'
Joplin	Westbound	I-44, 3	-0.2%	475'	1000'	1250'
Lehi	Eastbound	I-40, 273	+0.1%	725'	1250'	1550'
Marion	Southbound	I-55, 9	0.0%	1250'	1850'	2250'

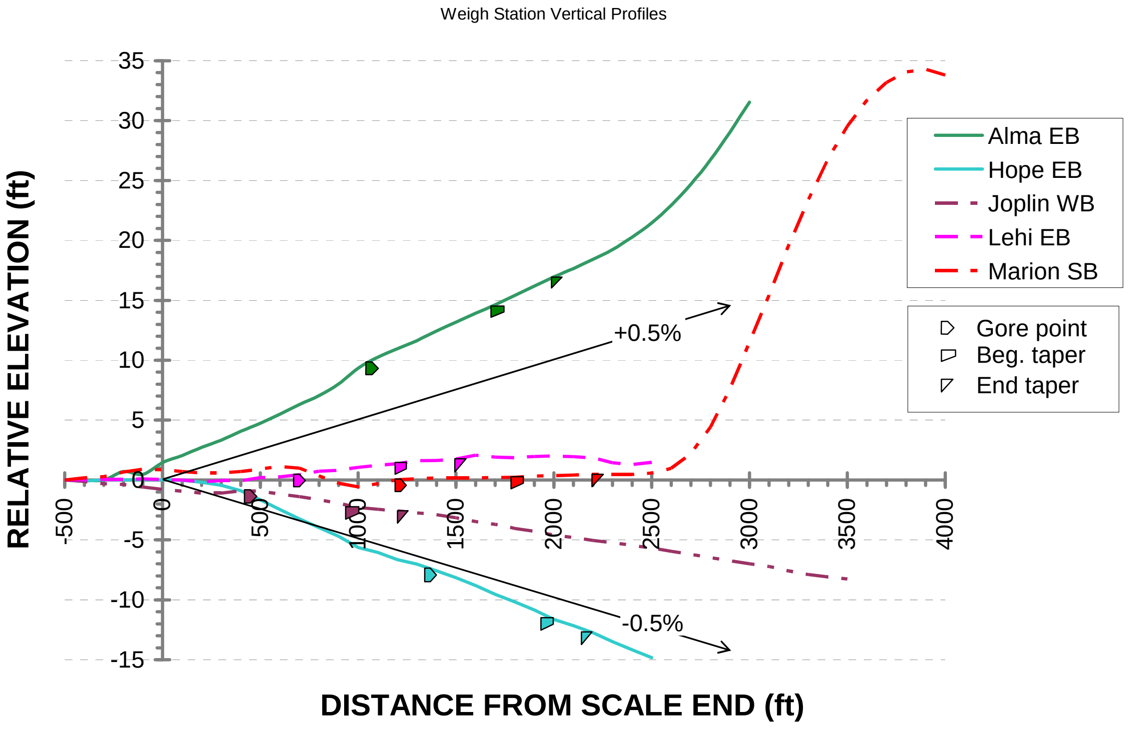

Figure 3-11: Vertical Profiles at Data Collection Sites

DATA COLLECTION PLAN

Once suitable locations for data collection were identified, the next step was to devise a data collection plan to record the speed, distance, time, and weight of the trucks as well as the volume of traffic on the freeway into which the trucks were entering.

Several different methods for collecting the desired data were examined. These methods included using standard video cameras, road tubes or magnetic sensors connected to vehicle classifiers, digital videography and Autoscope image processing technology, radar speed measurement devices, and laser speed measurement devices.

After examining the benefits and limitations of each method it was decided that using a laser speed measurement device called a lidar gun would provide the most detailed and accurate data for the speed and distance measurements of the trucks, and that standard video cameras would be used to record the weights of the trucks, the volume of traffic on the freeway, and the actions of the lidar gun operator.

The acronym lidar stands for light detecting and ranging. These guns measure the amount of time it takes for light pulses from a laser to reflect off of an object and return to the gun. By taking multiple readings, these guns can determine the speed of a vehicle and the distance from the operator of the gun to the vehicle several times per second. According to the manufacturer's specifications, the readings from the Stalker lidar guns used for the data collection were accurate to within ±1 foot and to within +1 mph to -2 mph (Stalker 2008). Connecting the lidar gun to a laptop computer allowed the observer to record multiple readings per second using a specially designed computer program. These readings consisted of the truck's speed, distance from the observer, and time at which the measurement was taken.

The lidar gun operator would be positioned near the weigh station scales and would measure the tractor-trailer trucks from behind as they accelerated from the scales. A video camera would be positioned behind the lidar gun operator to record the event, and to help determine the quality of the readings later on. A second video camera would be aimed toward freeway traffic, to record the freeway volume. A third video camera would be located inside the weigh station building to record the weights of tractor-trailer trucks that passed through the weigh station. This video camera would have a view of the trucks as they passed the weigh station building and would record the voice of a data collection team member audibly announcing the weight of each truck.

The data collection required that the camcorders and laptop computers used to collect the data to be synchronized so that the multiple data sources could be correlated and reviewed. By using the lidar gun connected to a laptop computer and standard video cameras, this problem was minimized because all of the equipment could easily be synchronized to approximately the same time. The potential errors in synchronizing the multiple pieces of electronic equipment included variation in the incremental accuracy of the time keeping mechanisms, and error incurred while setting the time of subsequent equipment pieces to match the first piece.

FIRST PILOT TEST

In order to identify problems with the proposed data collection plan and to identify potential changes, the researchers collected data at a nearby weigh station in Springdale, Arkansas. During this inspection, it was determined that one observer using a lidar gun could not capture the entire acceleration event of a tractor-trailer truck passing through the weigh station and entering the freeway. This was due to the fact that lidar guns have a small target area in which they measure, even at large distances. Before the trucks had finished accelerating, they became too small of a target to maintain measurement with the lidar gun. To ensure that data were collected up to the time at which the truck had accelerated to freeway speed, it was decided that a second observer using a lidar gun and laptop computer would be placed at a position some distance past the first observer. The data from the two lidar guns would then be merged to describe the entire acceleration event of the truck.

The test also confirmed that to record the weights of the trucks, an observer located in view of the weight readout device could audibly call out the weights of the trucks to a video camera as they passed through the camera's field of view. This observer could also write down the weights of the trucks that were measured by the lidar guns. Even though the Springdale weigh station did not have the weigh-in-motion system that four of the five selected data collection sites had, one possible difficulty in obtaining the truck weights using the weigh-in-motion system was noted during the inspection. The weigh-in-motion plates were located near the entrances of the weigh stations just after the deceleration lane. This meant that the truck weight would be displayed several seconds before the truck passed the weigh station building. If multiple trucks entered the weigh station closely following one another, it could become difficult to associate the correct weights with the correct trucks as they passed through the video camera's field of view.

There was also one problem noted during the inspection regarding the video camera that would be placed in the outer separation of the freeway to record the freeway traffic volume. The possibility was recognized that a large vehicle, such as a tractor-trailer truck or bus, could obstruct the view of one or more smaller vehicles in the left lane of the freeway.

EXPANDED PILOT TESTS

Expanded pilot tests were conducted at the Alma weigh station, because its proximity to Fayetteville. The main objectives of the pilot tests were to look for additional problems with the data collection plan and to determine the placement and orientation of the second lidar gun. Video cameras were not used during the pilot tests because the primary objective was to look for additional problems with the data collection plan, and there was no intention of using any data collected during the pilot tests in the final data set.

During the first pilot test, problems were encountered during the initial setup of the data collection equipment and no data were collected using the lidar guns. These problems were addressed by sending one gun to the manufacturer for repairs, and by acquiring a connection adapter.

During the second pilot test, data were collected using two different equipment placement/orientation scenarios to determine the best method of collecting data using two lidar guns. In the first scenario, the first lidar gun was placed before the static truck scales facing the direction of travel, and the second lidar gun was placed approximately 2300 feet past the static truck scales facing back toward the weigh station at the oncoming trucks. In the second scenario, the first lidar gun was placed in the same location, but the second lidar gun was placed approximately 1000 feet past the static truck scales facing away from the weigh station in the direction of travel of the trucks.

With the first scenario, the second lidar gun was not far enough away to measure the complete acceleration event, and it was difficult to correctly identify the truck that needed to be measured. The first scenario also required a large separation in trucks both in front of and behind the measured truck so that there were no obstructions for either lidar gun while taking the readings. Another problem with the first scenario was that it would be very difficult to combine the readings of the two lidar guns because they were pointing in opposite directions and measuring different ends of the truck.

The second scenario proved to be the better option for using two lidar guns, because the measurements could be taken for a much greater distance, the trucks to be measured could be more easily identified, only a large separation in trucks behind the measured truck was required, and the readings from the two lidar guns could be more easily combined because they measured the same end of the truck. This pilot test finalized the decision to use the second scenario as the equipment setup for the data collection process.

During the third pilot test, the second equipment setup scenario was used to collect data. The first lidar gun was placed 130 feet before the end of the static truck scales, and the second lidar gun was placed 1000 feet past the end of the static truck scales.

One important limitation regarding the use of lidar guns to measure the truck speed and distance was found during the pilot testing. The limitation was that several types of tractor-trailer trucks could not be measured consistently using the lidar guns. Trucks that were pulling flat-bed trailers or trailers with wire mesh back panels could not be measured because there was not a large enough surface area for the lidar gun to maintain measurement throughout the acceleration event. It was also hard for the lidar guns to maintain measurement of trailers with dark rear doors. This meant that the majority of the measured trucks in the data set would be pulling box type trailers, and that the distribution of the truck weights obtained from the data set could be skewed because the lightest tractor-trailer trucks are often pulling empty flat-bed trailers, and the heaviest tractor-trailer trucks are often pulling flat-bed trailers loaded with oversized equipment or materials.

EQUIPMENT LOCATION AND OPERATION DURING DATA COLLECTION

Data were collected at the five sites in late May, June, and July, 2007. At all sites, data were collected on either two or three separate days.

While each of the selected data collection sites had different physical characteristics, the placement of the data collection equipment was kept as similar as possible. At all of the data collection sites, the first lidar gun was positioned approximately 3 to 5 feet away from the right edge of the travel lane, that led to the static truck weight scales, at a distance of 130 feet before the end of the scales. A video camera was placed approximately 5 feet behind the first lidar gun operator so that they could indicate whether the reading that had just been taken was good or bad, and so that the behavior of the measured truck could be examined.

The position of the second lidar gun was the same for four of the five data collection sites. Physical limitations mandated the repositioning of the second lidar gun at the Hope data collection site. At all of the data collection sites other than Hope, the second lidar gun was positioned approximately 5 feet away from the right edge of the travel lane at a distance of 1000 feet past the end of the static truck weight scales. At the Hope data collection site, the second lidar gun was positioned in the outer separation of the freeway approximately 20 feet away from the left edge of the weigh station travel lane at a distance of 900 feet past the end of the static truck weight scales. A video camera was placed approximately 5 feet behind the second lidar gun operator so that they could indicate whether the last reading was good or bad, and the behavior of the measured trucks could be examined.

The geometries of the weigh stations were different, which meant that the distance between the static truck scales and the gore point of the acceleration lane leaving the weigh station was different for each site. This resulted in different positioning of the second lidar gun in relation to the gore point of the acceleration lane. The locations of the gore points with respect to the weigh station static scales can be seen in Figure 3-11. At the Alma, Hope, and Marion data collection sites, the second lidar gun was 100 feet or more before the acceleration lane gore point. At the Lehi data collection site, the second lidar gun was approximately two-thirds through the distance between the gore point and the beginning of the taper at the end of the acceleration lane. At the Joplin data collection site, the second lidar gun was at the beginning of the taper at the end of the acceleration lane.

A third observer inside the weigh station recorded truck weights. There were two scenarios for obtaining the truck weights. The first scenario was that the truck passed over a weigh-in-motion plate upon entering the weigh station, which displayed an estimate of the truck’s weight onto a computer monitor in the weigh station building. The observer would then call out the truck weight to a video camera as the truck passed through the view of the camera, and the truck would continue through the weigh station without stopping. The second scenario was that the truck was required to enter a different lane, pull onto the static scales, and stop until the actual weight was determined. In the second scenario, the truck weight observer would read the truck weight from the static scale display and call it out to the video camera.

To record the traffic volume on the freeway, a video camera was placed in the outer separation of the freeway, approximately 10 to 20 feet from the right shoulder of the freeway.

This video camera was positioned facing traffic at an angle so that the vehicles could easily be counted and classified upon reviewing the video.

Figure 3-12 is a graphical representation of the placement of the data collection equipment at each weigh station site. The drawings in Figure 3-12 are not to scale, but they do show the location of the second lidar gun with respect to the freeway acceleration lane.

SITE SURVEY

During the data collection sessions at each weigh station site, the research team used a transit and leveling rod to record relative elevations at 100 foot increments along the travel lane that passed through the weigh station and the freeway after the weigh station acceleration lane. The readings began 500 feet before the end of the weigh station static truck weight scales and extended to between 2500 and 4000 feet past the scales, depending on the site. The distances between the static truck weight scales and the acceleration lane gore point, the beginning of the acceleration lane taper, and the end of the acceleration lane taper were also measured during the process. The relative elevations and measured distances were then used to find the gradient of the roadways.

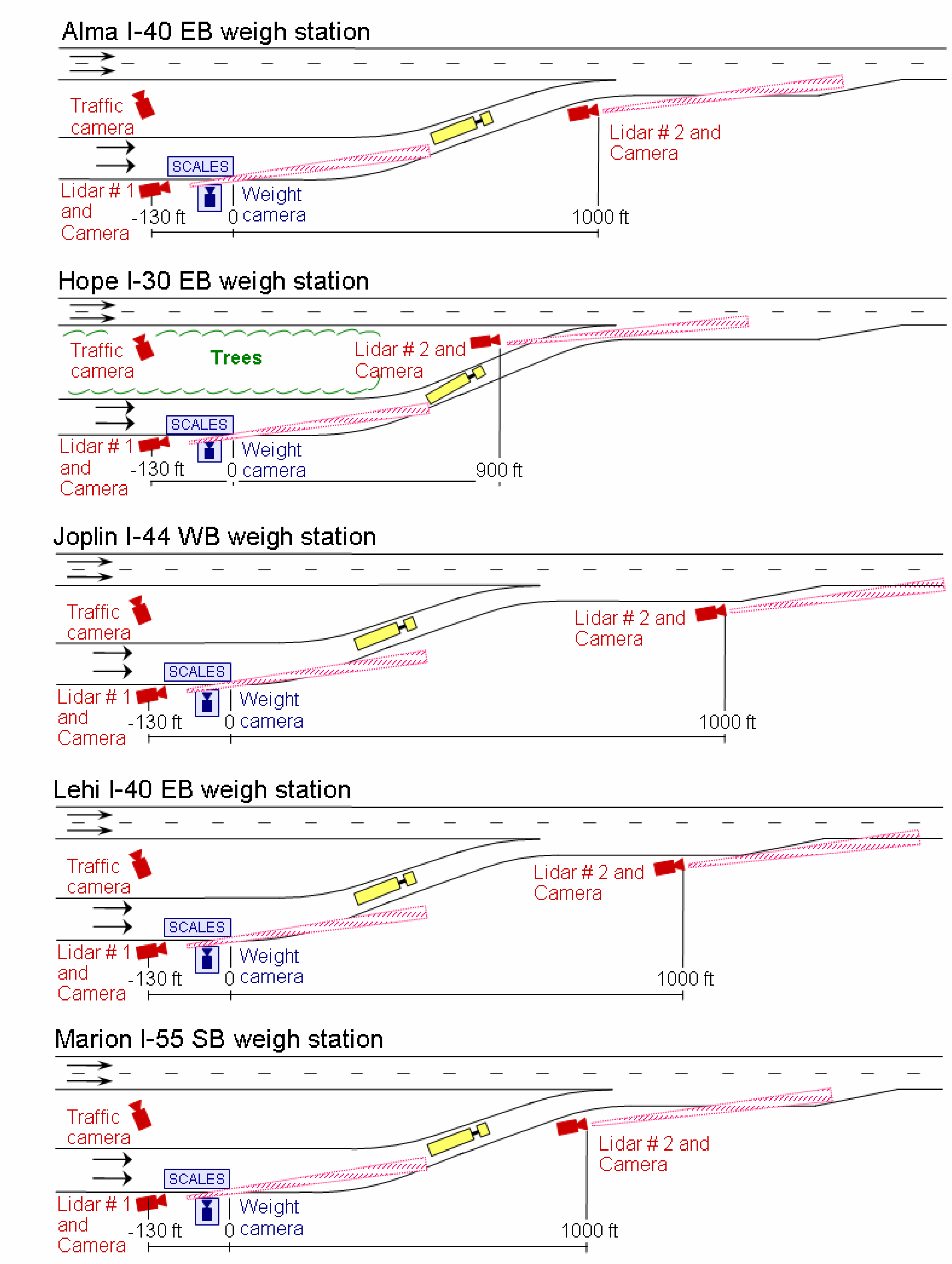

Figure 3-12: Equipment Locations at Data Collection Sites

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CHAPTER 4

DATA REDUCTION

Data reduction consisted of reviewing data collection videos, formatting the lidar gun data, and correlating the recorded truck weights and five minute freeway volumes to the electronic data.

REDUCE DATA FROM VIDEOS

The initial step in the data reduction was to watch the data collection videos and record the information from them. The first videos watched were the lidar gun videos. The indications made by the lidar gun operator about the measurement of each truck were recorded. The operators were instructed to use hand gestures to indicate whether the measurement for the truck was good or bad, and if it contained errors due to lidar gun malfunction. The intent of these actions was to aid in the segregation of the electronic data into good data and bad data.

The freeway volume camera videos were examined next. The number of vehicles in each five minute segment of data collection was counted. The freeway vehicles were classified as passenger cars, single-unit trucks, buses, or tractor-trailer trucks. The number of vehicles in each group was then summed for the four groups to obtain the total number of vehicles in that five minute segment.

The final videos reviewed were the truck weight videos. The information from these videos included the weight of the truck measured at the weigh-in-motion plates or at the static scales, the time at which the truck weight was taken, a short description of the truck, and whether or not the truck speed had been measured by the lidar guns.

ARRANGE LIDAR DATA

The second portion of the data reduction process involved the formatting the speed and distance data recorded by the lidar guns. The readings from the lidar guns had been recorded onto the laptop computers by a specially designed computer program. The program was designed to receive the speed and distance readings from the lidar gun, associate a time with the readings, and then record the data in a text (.txt) file on the computer.

The speed readings were recorded in even mile per hour increments with either a + or – in front of the numbers to indicate whether the vehicle was coming towards or moving away from the operator. The distance readings were recorded in even foot increments. The time readings were recorded in twenty four hour format.

The next step in the data reduction was to import the data from the text files into a spreadsheet where they could be organized and analyzed. The first column of the spreadsheet contained the + or – used to indicate the direction of the truck with respect to the lidar gun. The second column of the spreadsheet contained the truck's speed. The third column of the spreadsheet contained the distance from the lidar gun to the truck. The fourth column of the spreadsheet contained the entire time entry, and the fifth column contained only the number of seconds from the time entry. The data from the second lidar gun were placed to the right of the first lidar gun data, and the two sets were separated by two empty columns. Individual files called workbooks were created for each data collection site, and individual days at the same site were given different spreadsheets within the workbooks. These files were named using the last date that the file was modified and the name of the data collection location.

Once the files had been created, the data were separated into groups of individual truck readings through the use of alternating text colors to separate trucks. Highlighting was used to indicate bad data. The notes obtained from watching the lidar gun videos aided in determining whether data were good or bad. Then a new spreadsheet was created for each day on which data collection occurred so that the individual truck readings from the first and second lidar guns could be combined into complete truck acceleration events.

To combine the lidar gun data into events, a sequential vehicle number associated with the data collection site was placed preceding each event, and then the time values of the entries were used to roughly align the two sets of data for each truck. This was done by copying them from the raw data spreadsheet and pasting them into the combined data spreadsheet. The sets were aligned side by side so that the amount of overlapping data could be seen, and space was left between each event so that the alignment of the sets of data could be adjusted easily. The alignment of the data sets for each event was then refined using the speed and distance values of the entries to decide where to make the transition between the data from the first lidar gun and the second lidar gun. It was desired that the transition point chosen create a smooth transition between the data sets. To do this, a location was chosen where the speed value from the last entry of the first lidar gun data and the speed value from the first entry of the second lidar gun data were as close as possible, and the difference between the distances at which the two entries occurred was also as small as possible.

Once the transition point had been chosen, a new group of columns beside the aligned data sets was created so that the data for each event would be in a set of continuous columns. The speed values from each event were copied into the first column. The second column contained an equation that calculated the distance at which each entry occurred from the end of the static scales by either subtracting or adding the distance between the lidar gun and the scale end to the recorded distance value of the entry. The number of seconds associated with each entry was then copied into the third column. The fourth column was used if the time value changed minutes during the event. If the number of seconds reached sixty, an equation was used so that the number of seconds would continue to be sequential. The fifth column contained an equation that subtracted the initial time value of the event from the time value associated with the current entry so that the elapsed time was the result.

Because the lidar guns took multiple readings per second and the distance values reported by the guns were in even foot increments, the resultant data sets included duplicate distance values for sequential entries. Since these points would overlap when examining the data, and therefore provided no additional information, it was decided to remove them from the data set. This would also reduce the number of entries in each acceleration event, which would make them easier to analyze and manipulate. To remove the entries with duplicate distance values, a series of “if” statements were used to copy only the values from the first entry into a new group of columns. The statements compared the distance value of the previous entry in the event to the distance value of the current entry in the event. If the distance value was the same, then the values for the entry were replaced with blank cells in the new column group. If the distance value was different, then the values for the entry were copied into the new column group exactly as they appeared. This process resulted in several blank entries in each event. To remove these blank entries, the entire event was copied and then pasted into another new group of columns using the paste special function so that the values and not the “if” statements were copied. The sort ascending function was then employed on each event to reorder the entries in the event. The ones with values in them were placed together at the beginning, and the blank entries were moved to the end. The values for distance were used to sort the entries into ascending order.

INCORPORATE TRUCK WEIGHTS

The next task was to associate the recorded weights with each truck acceleration event. To do this, the times that were recorded by the truck weight camera operator had to be changed to match the times of the truck weight camera video and the lidar gun data. This was because the written weights were recorded using the time shown on the weigh station equipment which was not synchronized with the data collection equipment.

The first lidar gun camera video was examined simultaneously with the truck weight camera video, and a measured truck with a weight that was called out clearly was located. The corresponding entry recorded by the truck weight camera operator was located and the time difference was computed. The computed value constituted a factor that converted recorded time in one file to the recorded time in another file. This process was repeated approximately three times for each data collection session so that the correct truck weights were used.

The time at which each event began was then located in the file, found in the recorded truck weights, and a weight was associated with each event. If discrepancies were encountered between the written weight values recorded by the truck weight camera operator and the audible ones obtained from the truck weight camera video, the written one recorded by the truck weight camera operator was used. If an entry was missing from the written weights recorded by the truck weight camera operator, then the audible one from the truck weight camera video was used. If the weight of a truck could not be determined, then the event was marked for exclusion from the final data set.

During the process of correlating the tractor-trailer truck weights with the electronic acceleration event data, information from each acceleration event was recorded for a summary table. This information included the acceleration event number, truck weight, five minute freeway volume, and truck speed at multiple distances. The intention of the summary table was to aid in the statistical analyses performed on the data set.

PREPARE THE DATA FOR ANALYSIS

The data files required formatting so they could be analyzed by statistical software. Also, a second set of data were created with certain questionable acceleration events removed, and the two data sets were compared.

Reduced Data Set Files

After the procedures described above had been performed on all of the data from a data collection site, a reduced data set file for that location was created. Before importing the research data from the spreadsheet into the statistical analysis computer program SAS®, new files were created with the words "Format For SAS" included in the title. The information copied into these files consisted of the acceleration event number, truck weight, and the combined and filtered lidar gun readings. A summary table based on all of the data at the data collection site was constructed using the data recorded during the truck weight correlation, and included in the file.

Refining the Data

It was decided that a refinement in the data set could result in a more accurate prediction from the data, and a statistical analysis that contained less error. To perform this refinement, the data set was examined with the intention of removing the readings of trucks that were impeded by other trucks, or whose merge behavior was affected by outside influences. By removing these readings, the statistical analyses could be performed again on the data set, and differences in the two sets of results could be analyzed.

To remove these readings, the videos taken from the position of the second lidar gun were reviewed to observe the behavior of individual trucks. The times at which each of the trucks in the data set passed the cameras at both lidar gun positions were located in the spreadsheet files that made up the completed research data set, and recorded. The times at which the trucks passed the first lidar gun camera were recorded in case further examination of an individual truck's behavior needed to be performed. During the review of the videos, the behavior of each truck in the data set was examined and the situation in which it merged into the freeway was described as much as possible.

Several pieces of information were recorded for each truck. First, the approximate headway in seconds between the front bumper of the measured truck and the front bumper of the truck that preceded it was recorded. If the preceding truck was far enough ahead so as to not create an influence on the measured truck, the headway was recorded as not applicable. Because the position of the camera in relation to the acceleration lane varied from site to site, the headways were measured beginning either when the trucks passed the gore point of the acceleration lane or when they passed the camera. After examining video of several of the measured trucks, it was decided that trucks with headways equal to or less than seven seconds were more likely to have been influenced by preceding trucks and therefore needed to be removed from the data set.

Next, a comment regarding whether or not the measured truck displayed any obvious problems while merging was recorded. After that, an estimation of the location on the acceleration lane at which the measured truck merged into the main lanes of the freeway was recorded. Finally comments describing the presence and location of vehicles in the main lanes of the freeway when the measured truck either arrived at the acceleration lane or passed the camera were recorded. These comments included the number of passenger cars and/or tractor-trailer trucks in front of, beside, or behind the measured truck, the freeway lane that the vehicles were in, and the amount of time separating them from the measured truck. These times were referenced either from the gore point of the acceleration lane or the location of the camera.

If a vehicle in the right freeway lane was three seconds or less ahead of or behind the measured truck, or if there was a vehicle beside the measured truck, the readings for that truck were removed from the data set. It was decided that vehicles that were in the left freeway lane usually did not affect entry behavior, so the readings for these instances remained in the data set. It was also decided that vehicles in the freeway main lanes that were more than three seconds behind the measured truck would not create a negative influence on the truck, and therefore the readings for these instances were also left in the data set.

Using the seven second rule for truck following headway, the three second rule for freeway vehicle to truck headway, and the comments recorded for each truck, a decision was made as to whether the truck’s data should be included in or excluded from the filtered data set.

As mentioned before, the variation in location of the camera in relation to the acceleration lane at the different data collection sites created some problems with the analysis of the second lidar gun videos. The second lidar gun positions were located 1000 feet past the weigh station static scales at every data collection site except Hope, where it was located 900 feet past the weigh station static scales. The distance between the weigh station static scales and the beginning of the acceleration lane varied between the data collection sites. This led to problems in analyzing the videos because the location of the acceleration lane in the field of view of the camera, and what features of the roadway could be seen, were different for each location.

At the Alma site, the second lidar gun camera was located 100 feet before the acceleration lane gore point on the right shoulder of the traffic lane leaving the weigh station. This camera location provided a good view of both the acceleration lane and the freeway main lanes.

At the Hope site, the second lidar gun camera was located 500 feet before the acceleration lane gore point in the depressed grass outer separation between the freeway main lanes and the traffic lane leaving the weigh station. This camera location did not provide a good view of the acceleration lane or the freeway main lanes because of the distances from the camera to the freeway and the camera to the acceleration lane. The elevation of the camera also affected the view because it was lower than both the freeway and the traffic lane leaving the weigh station.

At the Joplin site, the second lidar gun camera was located 525 feet past the acceleration lane gore point at the beginning of the taper that ended the acceleration lane, on the right shoulder. This camera location did not provide a good view of the truck’s merging behavior or the distances separating the measured truck from other vehicles because the measured truck had already merged by the time it passed the camera. This camera location did however have a clear view of the freeway after the acceleration lane.

At the Lehi site, the second lidar gun camera was located 275 feet after the acceleration lane gore point on the right shoulder. This camera location provided a good view of the freeway main lanes and the last half of the acceleration lane, however, many of the measured trucks had already merged by the time that they passed the camera.

At the Marion site, the second lidar gun camera was located 250 feet before the acceleration lane gore point on the right shoulder of the traffic lane leaving the weigh station. This camera location provided a good view of both the freeway main lanes and the acceleration lane.

The major challenges with viewing video from the second lidar camera were determining which lane through vehicles on the freeway were in, determining the location on the acceleration lane at which the trucks merged, and determining if the trucks purposefully slowed down or sped up to merge into the traffic flow.

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CHAPTER 5

DATA ANALYSIS AND RESULTS

The initial data analysis for this research began with independent analyses of recorded distances, truck weight, truck speed, and volume on the main freeway lanes. These analyses were completed using raw data from the completed data set and the results of preliminary statistical analyses performed on the completed data set. The fully reduced data consisted of computer files of good truck acceleration events, with weights correlated to them, that had been formatted for use in a statistical analysis computer program.

The statistician employed for this research used SAS® statistical software to perform multiple statistical analyses on the data set. The two objectives for the statistical analyses were to examine the effects that truck weight, freeway traffic volume, roadway grade, and data collection site had on measured tractor-trailer truck speed, and to develop equations that would predict truck speed at a given distance.

ANALYSIS OF RECORDED DISTANCES

In order to examine how far past the end of the static scales truck speeds had been recorded at each data collection site, speed profiles were created. The speed profile analyses, performed by the statistician, calculated the average, the minimum, the maximum, the 10th percentile, and the 90th percentile truck speeds at 100 foot intervals for each data collection site. The number of observations and the standard deviation within each interval were also determined. Using the number of observations in each interval, the percentage of observations remaining was calculated for each data collection site at four consecutive distances.

Table 5-1 shows that at all five of the data collection sites, 93% or more of the acceleration event distance readings extend to 2000 feet or more, and at four of the five data collection sites, 72% or more of the acceleration event distance readings extend to 3000 feet or more.

The Alma data set retained 79% of the observations at 3000 feet, but none at 4000 feet. This was due to an overpass located approximately 2500 feet past the weigh station static truck weight scales. As the trucks continued up the increasing grade of the freeway, the deck and support beams of the overpass obscured the view of the truck.

Table 5-1: Number of Observations in Research Data Set

	at 1000 ft		at 2000 ft		at 3000 ft		at 4000 ft	
	number	%	number	%	number	%	number	%
Alma EB	85	100%	83	98%	67	79%	0	0%
Hope EB	137	100%	128	93%	52	38%	0	0%
Joplin WB	41	100%	41	100%	39	95%	34	83%
Lehi EB	149	100%	141	95%	107	72%	36	24%
Marion SB	114	100%	111	97%	95	83%	74	65%

The Hope data collection site had the shortest acceleration event distance readings with only 38% of the observations extending 3000 feet or more. This was due to the placement of the second lidar gun in the outer separation of the freeway and overhanging foliage in the right-of-way that obstructed the view of the trucks.

The Joplin data collection site had the highest percentage of observations remaining at 4000 feet with 83%. This was a result of the geometry of the freeway, which was straight and slightly downhill, and the lack of obstructive roadway structures or foliage.

The percentage of observations remaining at the Lehi data collection site dropped from 72% at 3000 feet to 24% at 4000 feet because of an overpass support pier and multiple roadway signs which obstructed the view of the trucks. The roadway signs may have created some interference in the lidar gun readings due to their reflectivity. Interference of this nature would have caused the lidar gun to end continuous measurement of the truck.

The Marion data collection site had the second highest percentage of observations remaining at 4000 feet with 65%. There were no signs or structures that obstructed the view of the trucks at this location, but the measurements of the trucks were limited because the freeway grade rises to cross a roadway and railway at a grade separated intersection, and then descends. As the trucks passed over the crest of the hill, they became obstructed by either the freeway itself or the vehicles behind them.

ASSESSING WHETHER THE WEIGHT DATA WERE TYPICAL

The research team wanted to determine the degree to which the distribution of the weights in the collected data was representative of the weights that would be found at other freeway locations. To do this, they obtained weight data recorded by weigh-in-motion (WIM) plates at several locations throughout the state of Arkansas from the Arkansas Highway and

Transportation Department (AHTD). The WIM plate systems that the AHTD uses on its freeways are classified as Type II systems under ASTM specification E 1318 (ASTM 2002).

From among these WIM sites, weights from the Mayflower, AR, WIM station were selected to develop this database. Being in central Arkansas, it was felt that data from this site would not be atypical. Also, unlike other sites considered, data from this site were available for February, April, August, and November of 2006, which provided a sample from each of the four seasons of the year. Some of the other Arkansas WIM sites that were representative but rejected due to insufficient data were I-30 at the Pulaski County line, Lonoke, Arkadelphia, Brinkley, West Memphis, Glen Rose, Forrest City, and Gilmore.

The WIM data were filtered and converted using database software, so that the output consisted of only the weights of single unit trucks, tractor-trailer trucks, and buses at the Mayflower location during the months of February, April, August, and November of 2006. The final representative data set contained 1,283,909 weight entries. These values were imported into a spreadsheet, and a graph of the weights versus cumulative percentage of entries was constructed using the histogram data analysis tool. From this graph, seen in Figure 5-1, it was noted that most of the recorded weights were greater than 20,000 pounds, and few exceeded 110,000 pounds.

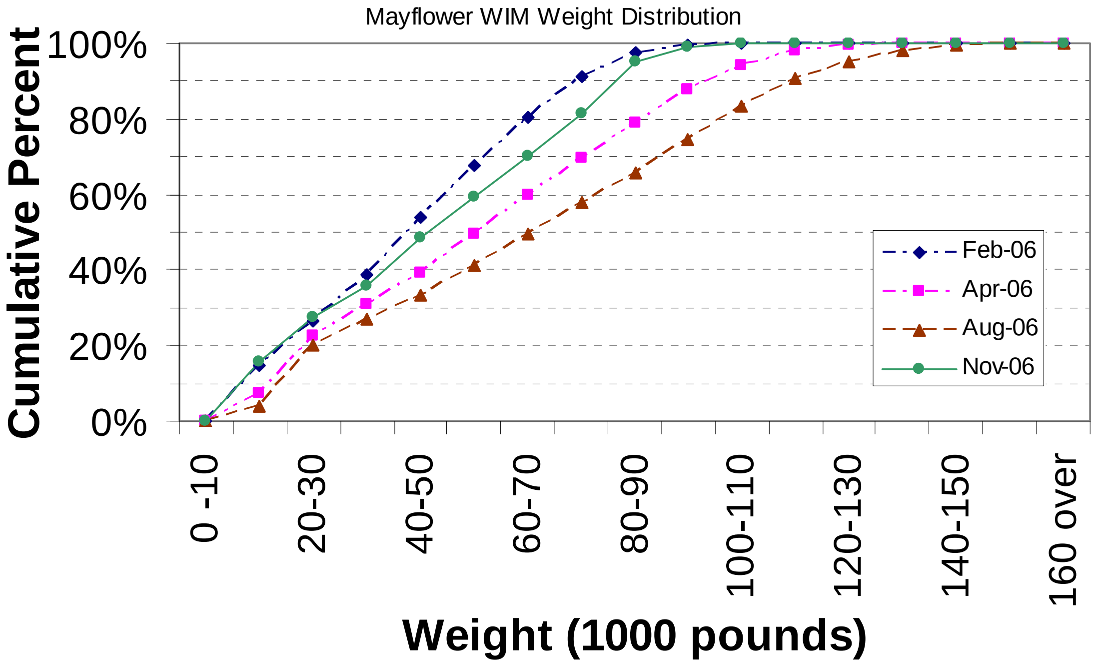

Figure 5-1: Weight Distribution at Mayflower WIM Station

The completed research data set initially consisted of 526 tractor-trailer truck weight entries, before the readings of impeded and potentially impeded trucks were removed. All 526 weight entries were used to construct the truck weight distribution graph in Figure 5-2. The figure shows both the distribution of the tractor-trailer truck weights in the research data set and the two extreme weight distributions from the Mayflower weigh-in-motion data.

The WIM data should be viewed with some considerations in mind. The accuracy of the gross-vehicle weight measurements for Type II weigh-in-motion plate systems is only required to be within 15% of the actual vehicle weight (ASTM 2002). The speed of the vehicle affects the accuracy of the measurements made by the system (ASTM 2002).

Tractor-trailer trucks can easily weigh over 10,000 pounds, even when unloaded. The maximum legal tractor-trailer truck weight without a permit in Arkansas is 80,000 pounds. As previously mentioned, certain types of tractor-trailer trucks could not be effectively measured using lidar guns. This must be a consideration when examining the figure because the weights of these trucks would probably fall into the lower and upper extremes of the weight distribution of the research data. Another consideration while examining the figure should be that the WIM data included several types of large vehicles, and the research data set only included tractor-trailer trucks.

Most of the truck weights in the research data set ranged from approximately 20,000 pounds to approximately 80,000 pounds. Given the expected weights of unloaded tractor-trailers and the maximum legal weight limit, these values seemed reasonable. From the figure, one can see that the distribution of the tractor-trailer truck weights in the research data set was fairly continuous and even across the range of weights measured.

The Mayflower WIM data with which the research data were compared had a somewhat greater percentage of vehicles at the low end of the weight range, and the August Mayflower WIM data contained a higher percentage of overweight vehicles. It is not known whether the August heat affected the WIM readings. Although the distribution of the weights in the collected data do not closely agree with those from the Mayflower WIM station, given the factors mentioned in the preceding paragraphs, the collected data do not appear to be outliers, and represent the central tendency of the majority of the truck weights.

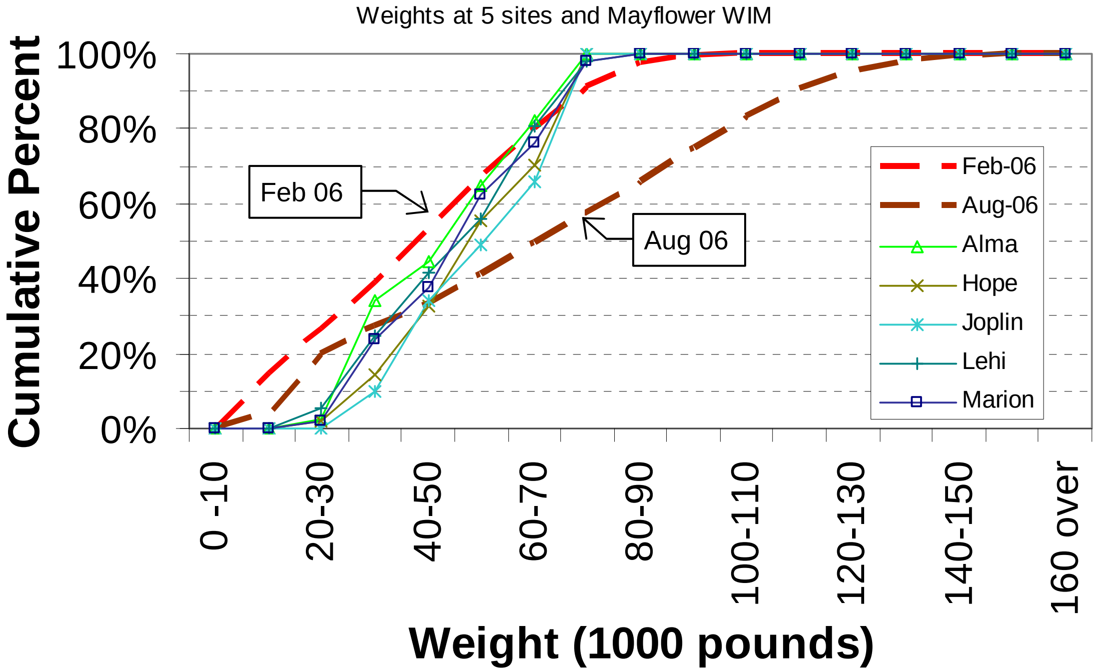

Figure 5-2: Research Data and Mayflower WIM Weight Distributions

ANALYSIS OF TRACTOR-TRAILER TRUCK SPEED

The objective of the speed analysis was to examine the progression of tractor-trailer truck speeds at each data collection site, and to compare speeds measured at fixed distances from the weigh station static scales to speeds measured in reference to the acceleration lane gore point. To perform these analyses, the speed profile data was once again queried. Truck speeds at several distances past the weigh station static truck scales and at the acceleration lane gore point plus several distances past the gore point were located and compiled into Tables 5-2 and 5-3.

Table 5-2: Recorded Tractor-Trailer Truck Speed from End of Static Scales

	at 1000 ft			at 2000 ft			at 3000 ft			at 4000 ft		
	min.	avg. (mph)	max.	min.	avg. (mph)	max.	min.	avg. (mph)	max.	min.	avg. (mph)	max.
Alma EB	23	34	44	33	47	58	38	53	63	n/a	n/a	n/a
Hope EB	17	38	48	35	51	64	48	60	69	n/a	n/a	n/a
Joplin WB	23	37	45	39	50	58	49	57	67	51	62	71
Lehi EB	25	38	51	39	49	60	44	56	66	52	61	67
Marion SB	20	38	49	39	50	57	45	55	64	45	55	65

NOTE: min. = minimum, avg. = average, and max. = maximum speed recorded at this location, Alma grade is +, Hope grade is -, Marion grade is + after 2600 feet

Table 5-3: Recorded Tractor-Trailer Truck Speed from Merging Gore

	at gore pt.			at gore pt. plus 1000 ft.			at gore pt. plus 2000 ft.			at gore pt. plus 3000 ft.		
	min.	avg. (mph)	max.	min.	avg. (mph)	max.	min.	avg. (mph)	max.	min.	avg. (mph)	max.
Alma EB		1100 ft.			2100 ft.			3100 ft.			4100 ft.	
	23	36	46	34	48	59	38	53	64	n/a	n/a	n/a
Hope EB		1400 ft.			2400 ft.			3400 ft.			4400 ft.	
	21	43	56	44	55	69	n/a	n/a	n/a	n/a	n/a	n/a
Joplin WB		475 ft.			1475 ft.			2475 ft.			3475 ft.	
	18	27	35	33	44	54	45	54	64	50	60	69
Lehi EB		725 ft.			1725 ft.			2725 ft.			3725 ft.	
	22	33	45	36	46	58	40	54	65	50	60	68
Marion SB		1250 ft.			2250 ft.			3250 ft.			4250 ft.	
	28	42	51	42	52	60	43	54	64	51	57	65

NOTE: min. = minimum, avg. = average, and max. = maximum speed recorded at this location, Alma grade is +, Hope grade is -, Marion grade is + after 2600 feet

From Table 5-2 it can be seen that the trucks' speeds were fairly consistent across the data collection sites at the distances measured from the static truck weight scales. The Alma data collection site was uphill, which resulted in slightly lower average truck speeds. The Hope data collection site was downhill, which resulted in slightly higher average truck speeds. The table also shows that at Joplin, Lehi, and Marion (up to 2600 feet, where the freeway was nearly level), that the average truck speeds were similar. The average truck speed at the Marion data collection site at 4000 feet is much lower than at the Joplin and Lehi data collection sites because of the grade separated roadway/railway crossing that begins around 2600 feet past the static truck weight scales.

Table 5-3 displays some of the same general trends as Table 5-2. The uphill Alma data collection site generally had lower average speeds at distances measured from the acceleration lane gore point, and the downhill Hope data collection site had higher average speeds than the other sites. While it does not appear from Table 5-3 that the ramp geometry immediately preceding the acceleration lanes at the data collection sites was a major factor in average truck speed at the acceleration lane gore point, it very well may be a significant factor in locations, such as freeway interchanges, that have more restrictive ramp geometries. Table 5-3 does show that overall distance measured from the weigh station static scales appears to be one of the major factors controlling the speeds of the tractor-trailer trucks. The Joplin weigh station, which had the shortest distance between the static truck weight scales and the acceleration lane gore point, had the lowest average speed. Progressing through the range of distances between static truck weight scales and acceleration lane gore points shows that the further away the gore point was from the static truck weight scales, the higher the average tractor-trailer truck speed was. Because of this, it was decided that the best reference point for further analyses would be the end of the weigh station static scales rather than the acceleration lane gore point.

The next step in analyzing the measured tractor-trailer trucks' acceleration events was to compare the minimum, the average and the maximum speeds of the measured trucks at the end of the acceleration lane to the speed limit of the freeway. To do this, the speed values at the end of the acceleration lanes were obtained from the speed profile analysis data. Table 5-4 gives the minimum, the average, and the maximum measured truck speeds, the freeway speed limit, and the distance from the static truck weight scales to the end of the acceleration lane for each data collection site. For the purposes of this thesis, the end of the acceleration lane is defined as the location where the tapered section at the end of the full-width acceleration lane begins.

Table 5-4: Tractor-Trailer Truck Speed at Acceleration Lane End

	truck speed			truck freeway speed limit	distance to accel. lane end
	min. (mph)	avg. (mph)	max. (mph)	(mph)	(feet)
Alma EB	29	44	56	65	1750
Hope EB	35	51	64	65	2000
Joplin WB	23	37	45	70	1000
Lehi EB	31	41	52	65	1250
Marion SB	38	48	55	65	1850

Table 5-4 shows that the average tractor-trailer truck speeds at the end of the acceleration lanes were more than 10 mph below the posted truck speed limit at all of the data collection sites. They ranged from 14 to 33 mph below the posted truck speed limit. The maximum tractor-trailer truck speeds at the end of the acceleration lanes were also less than the posted truck speed limit. They ranged from 1 to 25 mph below the posted truck speed limit. Three out of five of the maximum truck speeds were 10 mph or more below the posted truck speed limit. The three data collection sites where the maximum truck speeds were closest to the posted truck speed limit were the three sites with the largest distances between the static truck weight scales and the end of the acceleration lane. The minimum truck speeds at the end of the acceleration lanes ranged from 27 to 47 mph below the posted truck speed limits.

ANALYSIS OF FREEWAY VOLUMES

Five minute freeway volumes for both main lanes in one direction were determined during the data reduction using the traffic camera videos recorded during the data collection. In order to present the traffic volume ranges in which the research data were collected, the five minute volumes on the main freeway lanes were converted to equivalent hourly volumes, and are shown in Table 5-5.

Table 5-5: Traffic Volumes on Freeway during Data Collection

Site	Lowest 5 min. Flow rate (veh/h)	Average 5 min. Flow rate (veh/h)	Highest 5 min. Flow rate (veh/h)
Alma EB	696	979	1392
Hope EB	276	597	984
Joplin WB	312	563	936
Lehi EB	372	713	1404
Marion SB	420	879	1464

Table 5-5 lists the five minute freeway volumes expressed in terms of equivalent number of vehicles per hour. They ranged from 276 to 1464 vehicles per hour. The average hourly flow rates ranged from 563 to 979 vehicles per hour across the data collection sites.

Figure 5-3 shows the number of vehicles in each full five minute interval plotted against the time of day in which they were obtained. The majority of the data were collected between the hours of 9:00 a.m. and 12:00 p.m., and between the hours of 2:00 p.m. and 5:00 p.m. At the

Alma, Lehi, and Marion data collection sites, some volumes that were greater than 100 vehicles per five minutes, but the majority of the volumes were between 40 and 90 vehicles per five minutes at all of the data collection sites.

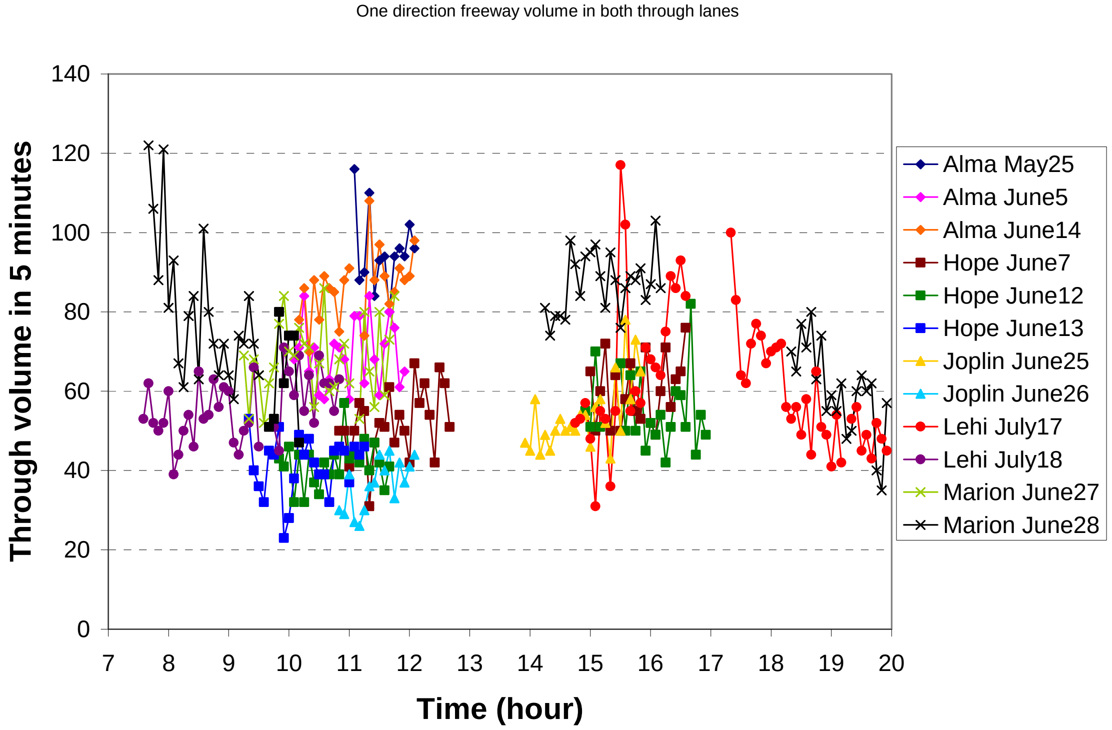

Figure 5-3: Five Minute Freeway Volumes during Data Collection

EFFECTS OF WEIGHT AND VOLUME ON SPEED

To examine the effects that truck weight and freeway volume had on the speed of the measured tractor-trailer trucks in the completed data set, two types of statistical tests were performed on the data. The tests were one-way analyses of variance (ANOVAs) and multivariate analyses of variance (MANOVAs). These tests were performed on the completed lidar gun data files from each data collection site. The objective of these analyses was to determine the significance of the effects that the truck's weight, freeway volume at the time that the truck merged into the flow of traffic, and interaction between the two had on the measured truck's speed. These effects were examined at three fixed distances within the study areas. MANOVAs were employed so that multiple dependant variables (distances) could be examined within the same model. The MANOVA models allowed the attributes of the data collection site as a whole to be tested because truck speeds at multiple locations within the data collection site were included in each model.

Conducting the MANOVA and ANOVA Tests

Two separate sets of MANOVA and ANOVA tests were performed on data from each site at 1000, 2000, and 3000 feet past the static truck weight scales. The first tests included all of the truck acceleration events in the completed data set for a site. The second tests used only the acceleration events that were determined to come from trucks that were unimpeded while merging into the flow of traffic on the freeway.

The initial step in the procedure was to perform a MANOVA test on the data from each site that included the interaction between truck weight and freeway volume. If the interaction was non-significant, then a MANOVA test that did not include the interaction between truck weight and freeway volume was performed. After the MANOVA without interaction had been performed, then ANOVA tests for each of the 1000-foot increment distances were performed without the interaction of truck weight and freeway volume. However, if the interaction in the initial MANOVA was statistically significant, then ANOVA tests for each distance were performed, with the interaction of truck weight and freeway volume included. If any of these ANOVAs returned interaction p-values that were not significant, ANOVAs without the interaction were performed at the 1000-foot increment distances.

Except for the cases described in the following paragraphs, the MANOVAs were performed with the dependent variables of truck speed at 1000 ft, speed at 2000 ft, and speed at 3000 ft. The independent variables were truck weight, freeway volume, and their interaction. Three separate ANOVA tests were performed, where the dependent variables were speed at 1000 ft, speed at 2000 ft, or speed at 3000 ft. The independent variables were truck weight, freeway volume, and their interaction. Where the preceding MANOVA test did not show the interaction to be significant, the interaction variable was not included.

A different procedure was used on the Hope data. Since this site lacked data at longer distances, the results of MANOVA tests were less reliable. Therefore, ANOVAs that included interaction were performed, even though they were not warranted by the results of the MANOVA that included interaction. This procedure was done for the analyses on the entire data set as well as the analyses for the unimpeded trucks only.

At the Marion site, because the ANOVA for truck speed at 1000 feet (entire data set) showed an interaction that was only marginally significant (p-value=0.0845), an ANOVA without interaction was also performed. Also, additional ANOVAs that included interaction were performed on the unimpeded truck data from the Marion site. These ANOVAs were performed because the initial MANOVA for the site returned a p-value of 0.1184 for interaction that was close to being significant, and the interaction term had been significant in the models that included the entire data set.

Tables 5-6 and 5-7 contain results of the MANOVA and ANOVA analyses. The p-values indicate whether or not a particular variable was statistically significant in the model. P-values less than 0.10 indicate a significant effect of the variable, while p-values greater than 0.10 indicate that the variable did not have a statistically significant effect.

From the p-values in Table 5-6, for the entire data set at distances measured from the weigh station static scales, 12 out of a possible 15 times truck weight was significant, and only three out of the possible 15 times was volume significant.

Table 5-6: P-Values from MANOVA and ANOVA Analyses on Entire Data Set at 1000, 2000, and 3000 Ft Past Static Scales

		MANOVA		ANOVA			ANOVA		
		with interaction	without interaction	without interaction			with interaction		
				speed 1000	speed 2000	speed 3000	speed 1000	speed 2000	speed 3000
Alma	weight	.9589	<.0001	.1514	<.0001	<.0001			
	volume	.5367	.8726	.8458	.9953	.7106			
	wt*vol	.5847							
Hope	weight	.2139	<.0001	.2012	<.0001	<.0001	.1593	.0027	.1128
	volume	.3602	.4212	.7591	.7909	.2608	.2273	.0338	.2644
	wt*vol	.5189					.2428	.0340	.3610
Joplin	weight	.2220	<.0001	.0073	<.0001	<.0001			
	volume	.2129	.2498	.7145	.8271	.3132			
	wt*vol	.2411							
Lehi	weight	.0012		<.0001	<.0001		.0457	.0020	<.0001
	volume	.0172		.9325	.9462		.3375	.1494	.0063
	wt*vol	.0162					.3119	.1324	.0055
Marion	weight	<.0001		.3761	<.0001	<.0001	.1431	.0998	.0106
	volume	.0008		.0558	.5956	.9045	.0297	.9413	.3321
	wt*vol	.0057					.0845	.8221	.3302

The p-values in Table 5-7, which were for unimpeded trucks at distances measured from the weigh station static scales, again show the generally truck weight was statistically significant and volume was not. The p-values show that 12 out of a possible 15 times, truck weight was significant, and only two out of the possible 15 times was volume significant.

While these analyses did show that the interaction between truck weight and freeway volume was statistically significant at a few of the locations analyzed within the entire data set, they did not explain what these interactions meant. To examine these interactions, additional analyses in the form of contour plots were performed.

Table 5-7: P-Values from MANOVA and ANOVA Analyses on Unimpeded Trucks at 1000, 2000, and 3000 ft Past Static Scales

	MANOVA		ANOVA			ANOVA		
	with interaction	without interaction	without interaction			with interaction		
			speed 1000	speed 2000	speed 3000	speed 1000	speed 2000	speed 3000
Alma 55.3% unimpeded								
weight	.4135	<.0001	.8291	.0002	<.0001			
volume	.3376	.9013	.6431	.9255	.8278			
wt*vol	.3034							
Hope 57.7% unimpeded								
weight	.4565	<.0001	.4997	<.0001	.0004	.5705	.1549	.2437
volume	.8609	.6917	.7630	.7339	.7940	.6152	.5997	.4758
wt*vol	.8594					.6573	.5417	.4969
Joplin 95.1% unimpeded								
weight	.2511	<.0001	<.0001	<.0001	<.0001			
volume	.3048	.1553	.9464	.4676	.1041			
wt*vol	.3285							
Lehi 63.1% unimpeded								
Weight	.1282	<.0001	.0025	<.0001	<.0001			
volume	.5666	.9578	.6408	.6321	.7801			
wt*vol	.5242							
Marion 41.2% unimpeded								
weight	.0015		.6140	.0005	<.0001	.9021	.0340	.0579
volume	.2197		.1343	.0561	.0718	.9099	.4096	.8089
wt*vol	.1184					.8059	.1889	.4917

Speed, Weight, Volume Contour Plots

When the interaction between truck weight and freeway volume was determined to be statistically significant by the ANOVA analyses, contour plots were developed from the data to help interpret the significance. The contour plots provided a graphical representation of the effect that truck weight and freeway volume had on the speed of the measured trucks.

Three contour plots were developed from the analyses on the fixed distances measured from the weigh station static truck weight scales. All three of the significant interaction p-values came from the analyses on the entire data set. These contour plots were developed for the Hope data collection site at 2000 feet, the Lehi data collection site at 3000 feet, and the Marion data collection site at 1000 feet past the weigh station static truck scales. Figures 5-4 through 5-6 are the contour plots from Hope, Lehi, and Marion, respectively.

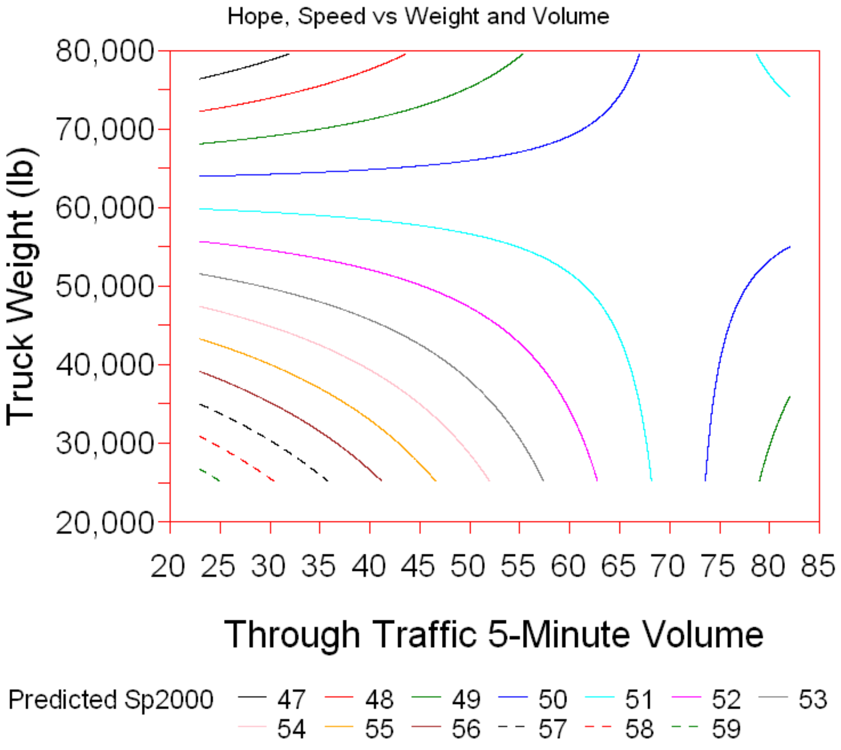

Figure 5-4: Contour Plot for Truck Speed at 2000 Feet at Hope Data Collection Site

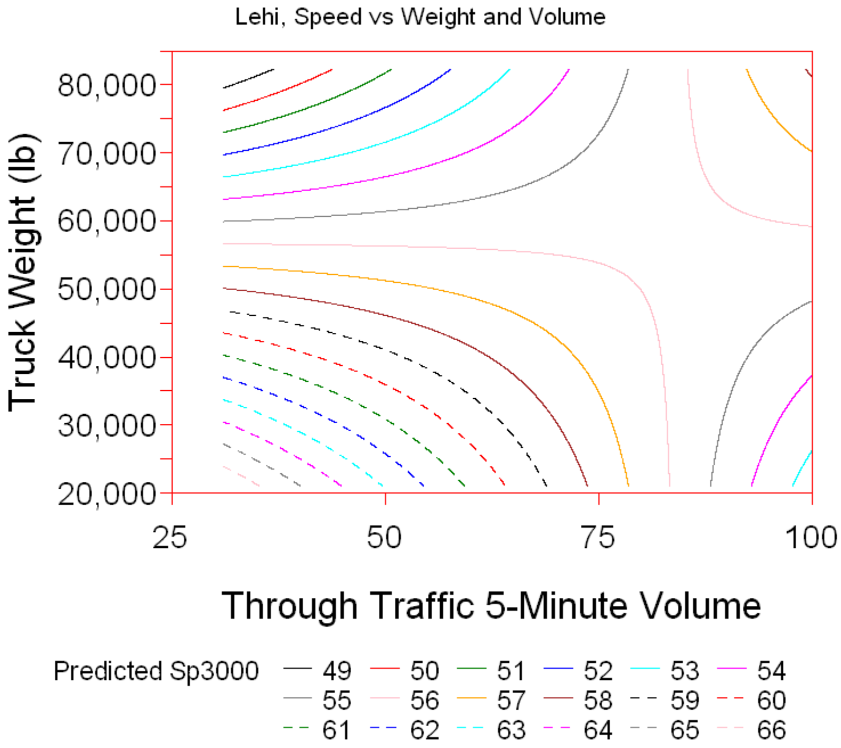

Figure 5-5: Contour Plot for Truck Speed at 3000 Feet at Lehi Data Collection Site

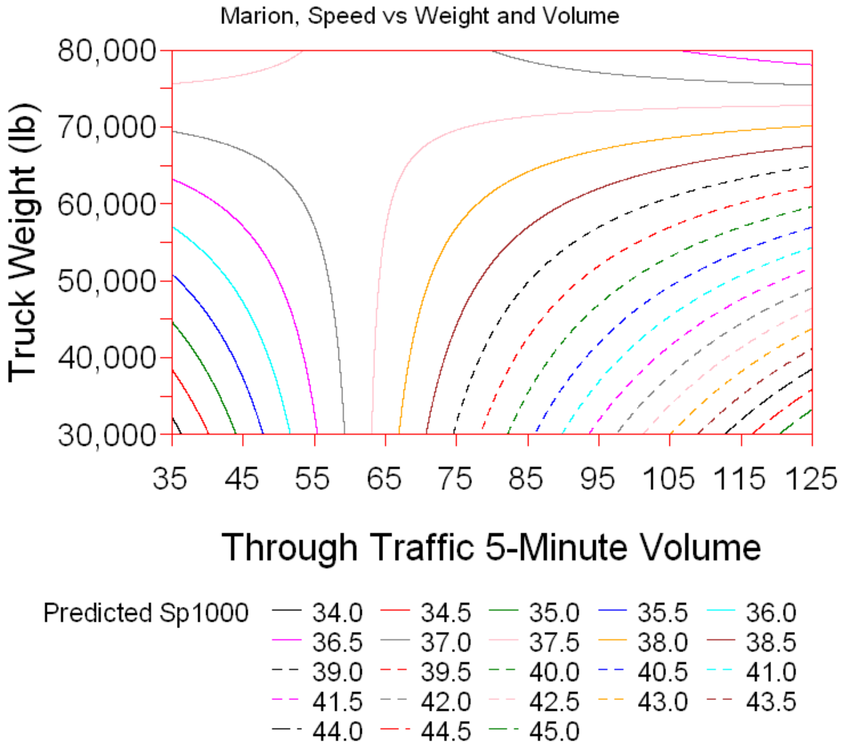

Figure 5-6: Contour Plot for Truck Speed at 1000 Feet at Marion Data Collection Site

As can be seen from these, the data divide the plots into quadrants. In each of these quadrants, the effects of truck weight and freeway volume on the speed of accelerating trucks were different. In Figure 5-4 and Figure 5-5 in the upper left quadrant, as truck weight increased truck speed decreased, and as freeway volume increased truck speed increased. In the lower left quadrant, as both truck weight and freeway volume increased, truck speed decreased. In the upper right quadrant, as both truck weight and freeway volume increased, truck speed increased. In the lower right quadrant, as truck weight increased truck speed increased, and as freeway volume increased truck speed decreased.

In Figure 5-6 in the upper left quadrant, as truck weight increases truck speed increases, and as freeway volume increases truck speed decreases. In the lower left quadrant, as both truck weight and freeway volume increase, truck speed increases. In the upper right quadrant, as both truck weight and freeway volume increase, truck speed decreases. In the lower right quadrant, as truck weight increases truck speed decreases, and as freeway volume increases truck speed increases.

COMBINING SITES FOR ANALYSIS

Because the Joplin, Lehi, and Marion (up to 2600 feet) data collection sites all have nearly level profiles, data from these three sites were analyzed to determine if they could be combined into a single data set that represented truck acceleration on nearly-level grades. The combined data could then be compared to the data from the uphill Alma site and the downhill Hope site.

A variable to indicate data collection site location was added to the data from the three sites, and additional MANOVAs and ANOVAs were performed. The analyses included the effects of data collection site, truck weight, freeway volume, and all of their possible interactions. As interactions were determined to be non-significant, they were removed from the models. The analyses were performed for measured truck speeds at both 1000 and 2000 feet past the static truck scales. Truck speeds at 3000 feet past the static truck scales were not included in the models because of the small sample size created by cutting the Marion data off at 2600 feet.

Tables 5-8 and 5-9 display the results. Mean values from the three sites were significantly different from one another. But the differences among the average truck speeds at 1000, 2000, and 3000 ft past the scales were less than two miles per hour, so the difference had little practical significance. Therefore, it was decided to combine the data from the Joplin, Lehi, and Marion (up to 2600 feet) data collection sites into a “level” data set for further analyses.

Speed Profiles

Two separate types of speed profiles were developed using the raw data from each of the data collection sites. The first type plotted speed versus distance for each individual truck acceleration event at each data collection site. The second type showed a single speed versus distance plot that represented the average of all of the truck acceleration events at that data collection site, along with upper and lower percentile values.

The initial speed profile graphs, which showed all of the truck acceleration events at each data collection site, were plotted using various colored lines to represent the events. The symbols that indicated the actual location of the data points within the lines were removed so that the data could be inspected more easily. Figures 5-7 through 5-11 show the initial speed profile graphs. The initial speed profile graphs allowed for a visual examination of the range of measured truck speeds at any given distance from the static truck weight scales, and allowed the continuity and consistency of the data to be checked for problems.

Table 5-8: P-Values from MANOVA and ANOVA Analyses on Entire Data Sets from Joplin, Lehi, and Marion (up to 2600 ft) Sites at 1000 and 2000 ft Past Static Scales

		weight	volume	site	weight volume	weight site	volume site	weight volume site
MANOVA		.0029	.8308	.0382	.7777	.1263	.2044	.3961
MANOVA		<.0001	.0123	.0016	.0058	.0141	.4006	
ANOVA	sp1000	.7102	.0849	.0102	.0991	.0326	.4635	
ANOVA	sp2000	.0024	.9766	.4361	.7713	.5455	.9928	
MANOVA		<.0001	.0017	.0012	.0057	.0108		
ANOVA	sp1000	.7648	.0370	.0128	.0969	.0203		
ANOVA	sp2000	.0023	.9711	.2932	.7683	.4966		
ANOVA	sp2000	<.0001	.3467	.1806		.3049		
ANOVA	sp2000	<.0001	.4584	.0626				
ANOVA	sp1000	.2356	.6413		.9136			
ANOVA	sp2000	<.0001	.3635		.2753			
ANOVA	sp1000	<.0001	.1824					
ANOVA	sp2000	<.0001	.6014					

Table 5-9: P-Values from MANOVA and ANOVA Analyses on Unimpeded Trucks from Joplin, Lehi, and Marion (up to 2600 ft) Sites at 1000 and 2000 ft Past Static Scales

		weight	volume	site	weight volume	weight site	volume site	weight volume site
MANOVA		.0004	.5206	.1508	.4044	.2074	.2393	.3273
MANOVA		<.0001	.0793	.0227	.0388	.0560	.4196	
ANOVA	sp1000	.9335	.4282	.0112	.5304	.0504	.4187	
ANOVA	sp2000	.0090	.6899	.1793	.4656	.3981	.2952	
MANOVA		<.0001	.0473	.0150	.0357	.0147		
ANOVA	sp1000	.8988	.3978	.0144	.5468	.0192		
ANOVA	sp2000	.0087	.6431	.1701	.4412	.3666		
ANOVA	sp1000	.0011	.2781	.0124		.0168		
ANOVA	sp2000	<.0001	.2379	.0527		.1465		
ANOVA	sp2000	<.0001	.3538	.0335				
ANOVA	sp1000	.1311	.4661		.3900			
ANOVA	sp2000	.0002	.0853		.0670			
ANOVA	sp1000	.0023	.6487					

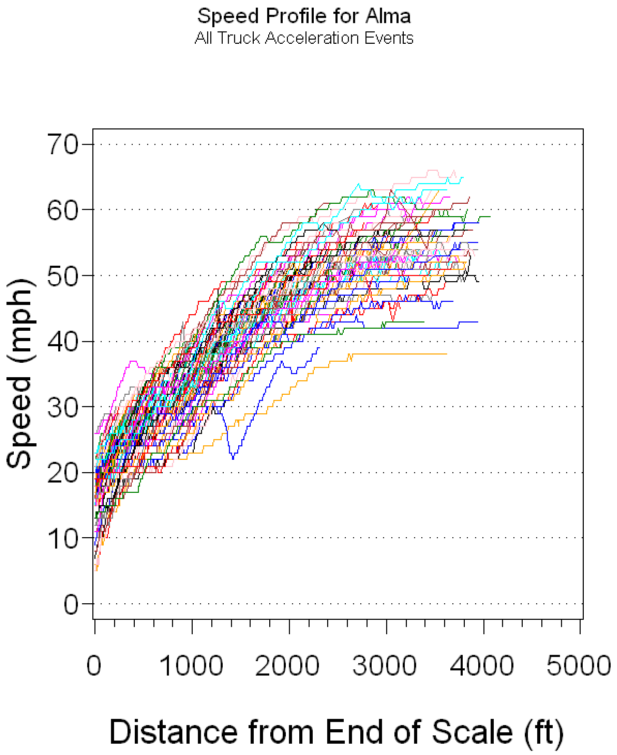

Figure 5-7: Initial Speed Profile for Alma Data Collection Site

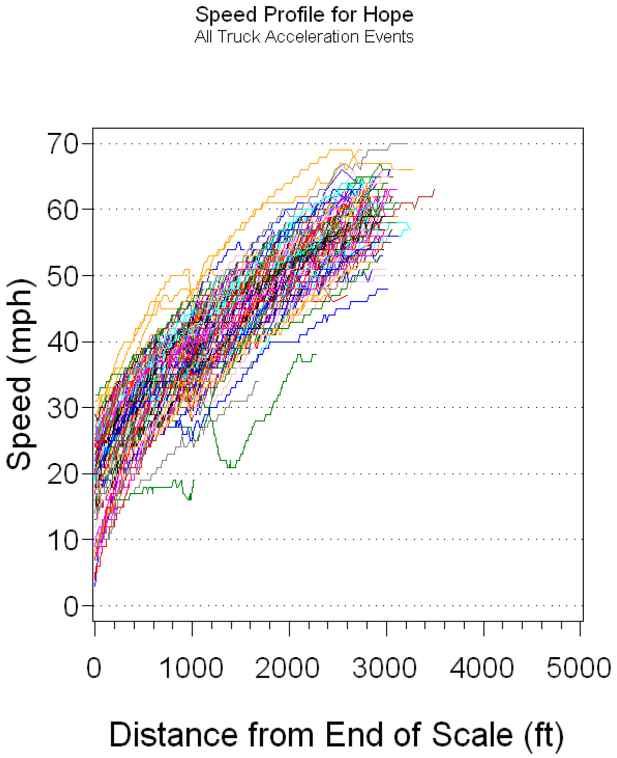

Figure 5-8: Initial Speed Profile for Hope Data Collection Site

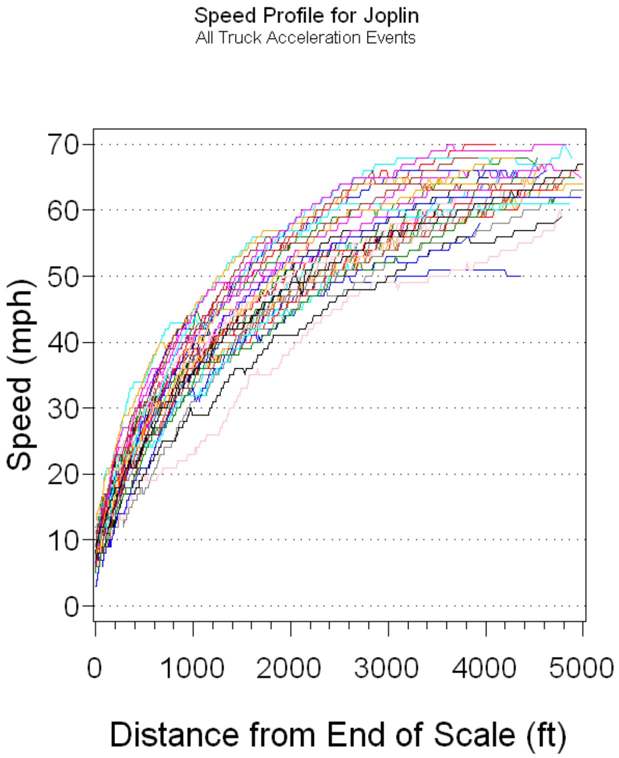

Figure 5-9: Initial Speed Profile for Joplin Data Collection Site

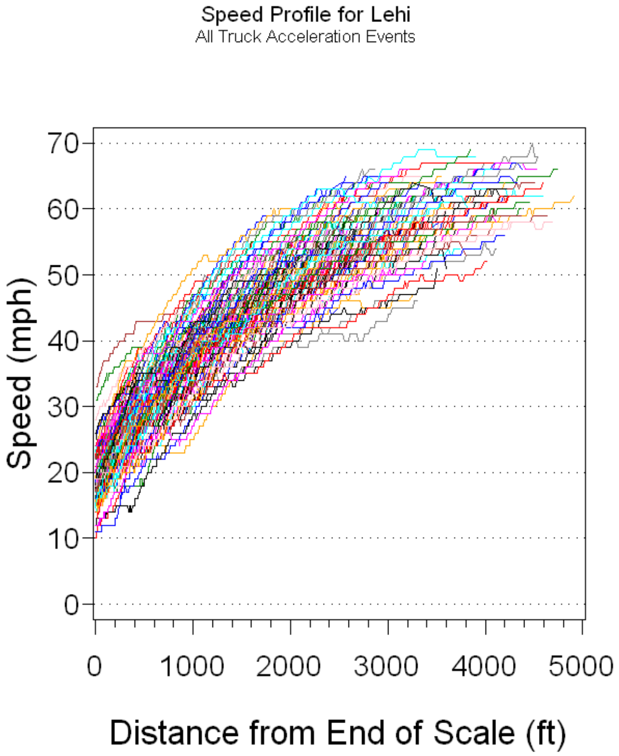

Figure 5-10: Initial Speed Profile for Lehi Data Collection Site

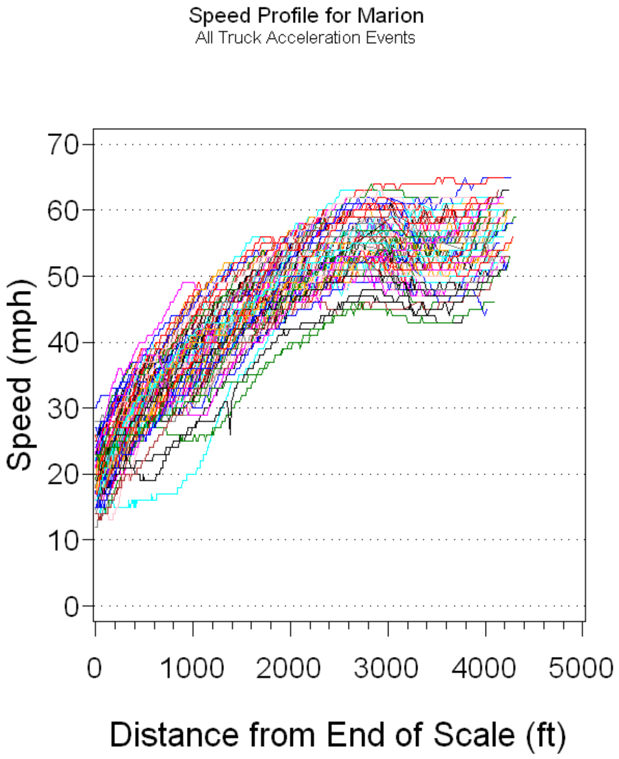

Figure 5-11: Initial Speed Profile for Marion Data Collection Site

Graphs of Average Speed Profiles

More graphs were constructed to show the profiles of average speeds at the sites. These graphs included profiles showing the 90th and 10th percentile speed values within the data.

In order to construct graphs of the average speed of the trucks at given distances, one must have speed readings from each truck at the same distances, such as all trucks must have a speed reading at 100 feet. But lidar readings for different vehicles are recorded at different spots. To address this problem, the speed values were aggregated into 100 foot intervals. The midpoint of each interval was an even multiple of 100 feet from the end of the static scale, and the bounds or ends of each interval were set at – 49 to + 50 feet. Therefore, all of the speed values taken for a truck at distances ranging from -49 feet to +50 feet were averaged to get the speed of that truck at 0 feet, the readings taken from +51 feet to +150 feet were averaged to get the speed of that truck x at 100 feet, and so on.

Once this procedure had been performed for each truck acceleration event at a site, the average speed for all trucks within each of the 100 foot intervals was calculated. These profiles were terminated when the number of readings at a given distance dropped to 10 or fewer.

This information was used to plot the following graphs of average truck speed versus distance from the weigh station static scales for each site. The procedure was also employed to construct averages for the combined data from the three “level” data collection sites.

The average speed profile for Alma (Figure 5-12) was terminated at 3900 feet past the static truck scales. The average speed profile for Hope (Figure 5-13) was terminated at 3100 feet past the static truck scales. The average speed profile for Joplin (Figure 5-14) was terminated at 4900 feet past the static truck scales. The average speed profile for Lehi (Figure 5-15) was terminated at 4500 feet past the static truck scales. The average speed profile for Marion (Figure 5-16) was terminated at 4200 feet past the static truck scales.

The average speed profile for the combined three “level” sites (Figure 5-17) was terminated at 4200 feet past the static truck scales. The termination point for this plot was determined by the extent of the data used from the Joplin data collection site in the “level” site analyses. The “level” site analyses also included data from the Lehi data collection site up to 3900 feet and from the Marion data collection site up to 2600 feet past the static truck scales.

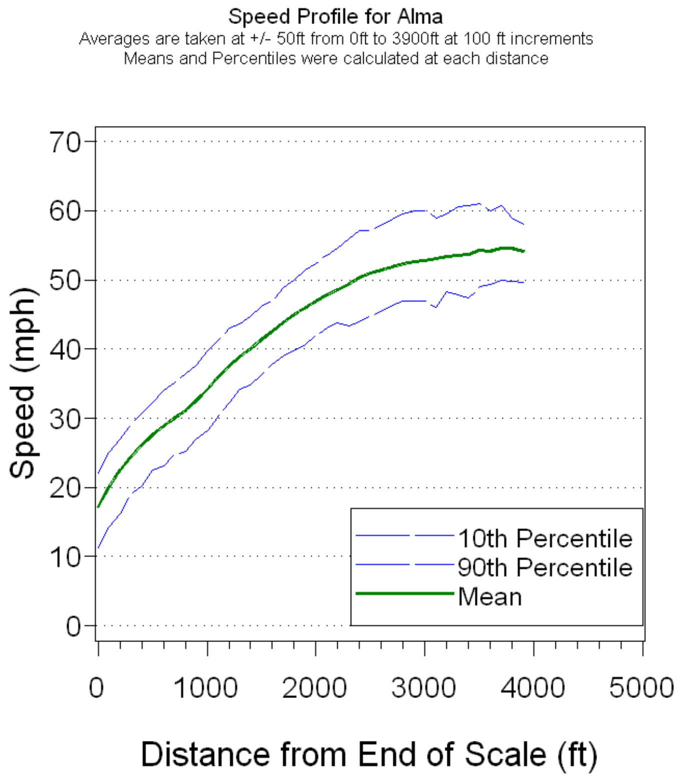

Figure 5-12: Average Speed Profile for Alma Data Collection Site

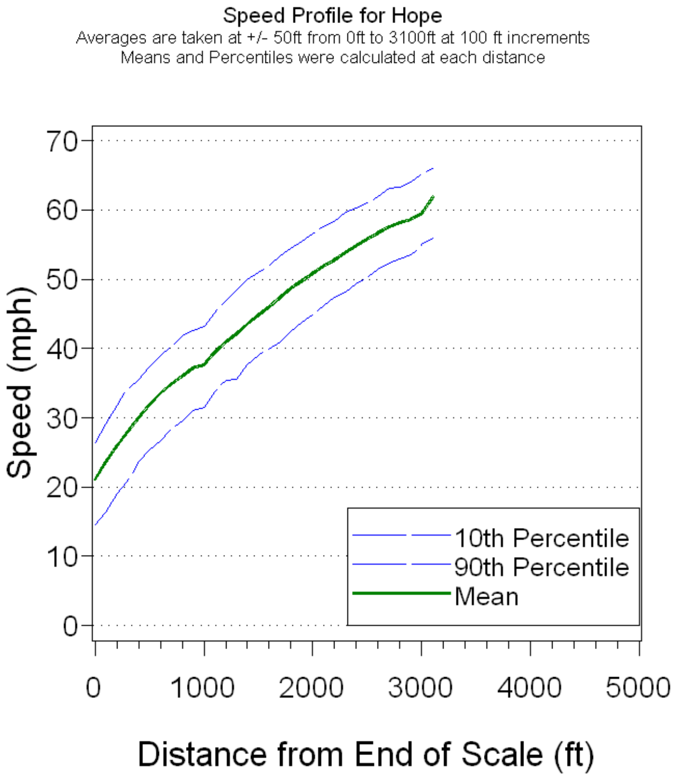

Figure 5-13: Average Speed Profile for Hope Data Collection Site

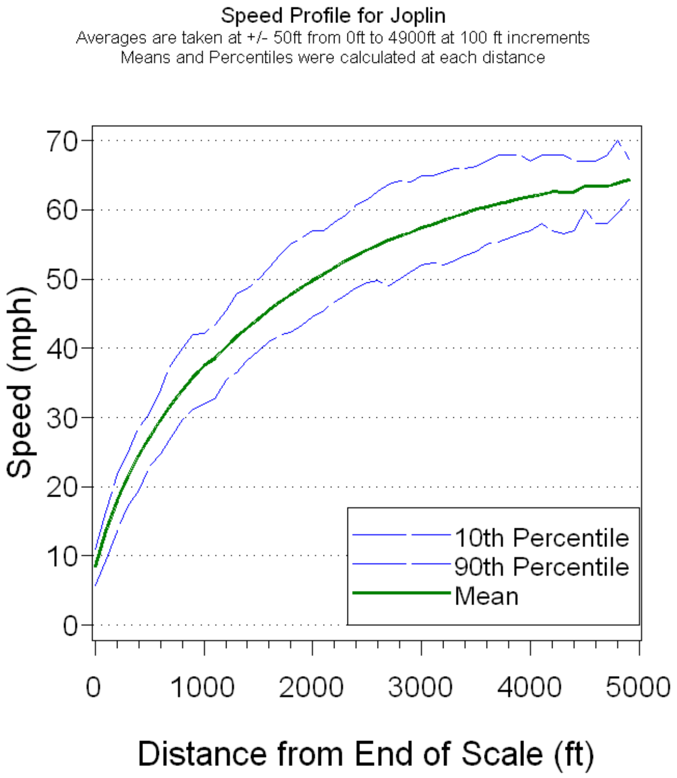

Figure 5-14: Average Speed Profile for Joplin Data Collection Site

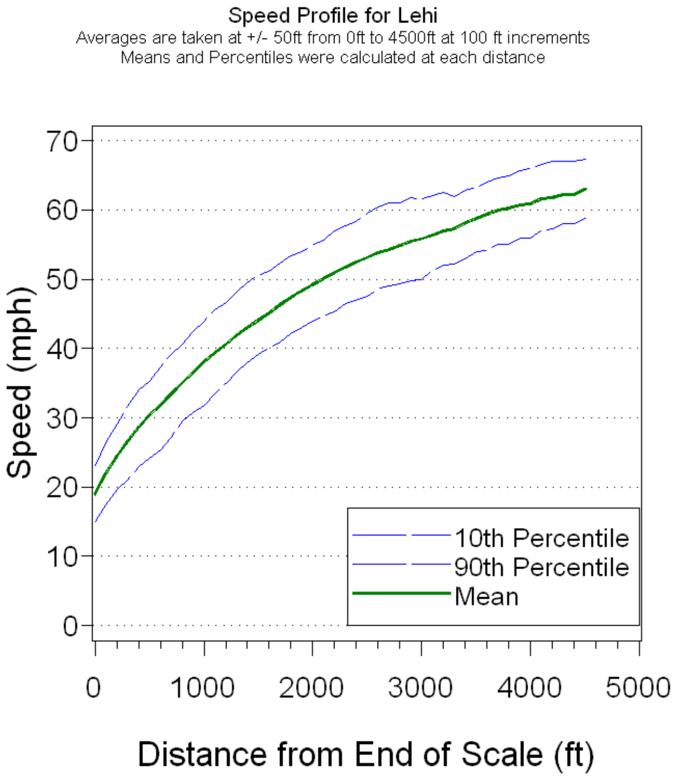
Speed Profile for Lehi
Averages are taken at +/- 50ft from 0ft to 4500ft at 100 ft increments
Means and Percentiles were calculated at each distance

Figure 5-15: Average Speed Profile for Lehi Data Collection Site

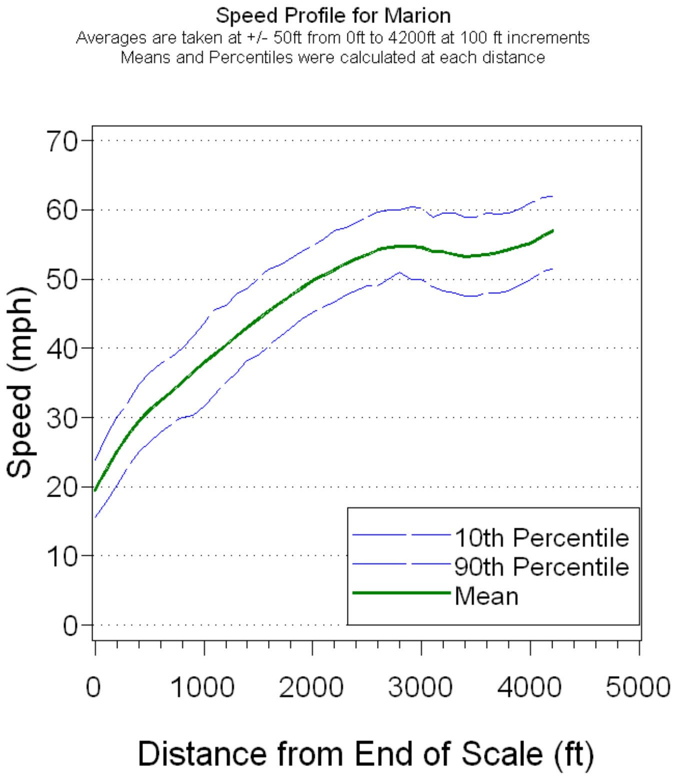
Speed Profile for Marion
Averages are taken at +/- 50ft from 0ft to 4200ft at 100 ft increments
Means and Percentiles were calculated at each distance

Figure 5-16: Average Speed Profile for Marion Data Collection Site

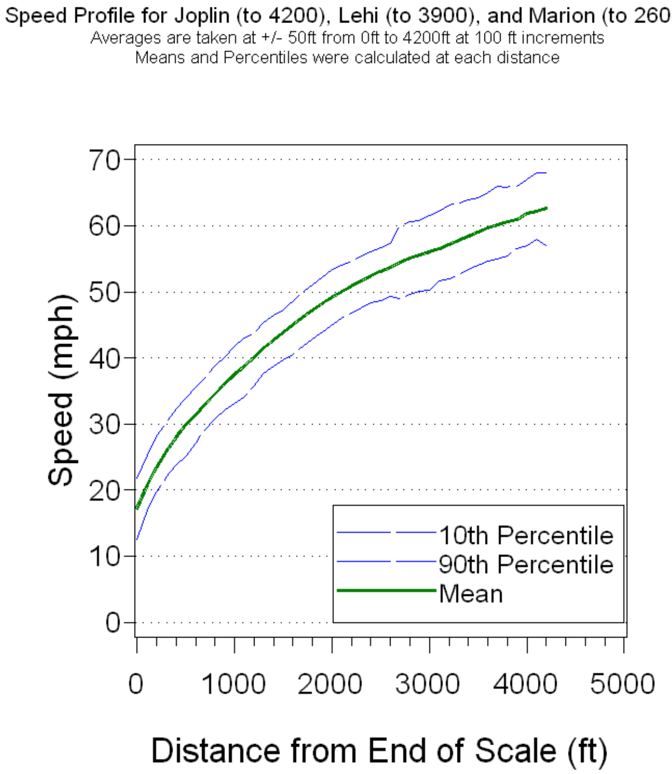

Figure 5-17: Average Speed Profile for Combined “Level” Data Set

TRUCK SPEED PREDICTION MODELS

The next step in the analyses was to develop mathematical models that predicted speed at a given distance for the “downhill” (Hope), “level” (Joplin, Lehi, Marion to 2600 feet), and “uphill” (Alma) data. Models were developed to predict average and 10th percentile truck speeds for both the “all” and the “unimpeded” acceleration events.

Models for Average Truck Speed

Since the lidar guns do not record speeds of different trucks at the same spot, simple linear regression could not be performed on the raw data to create a model. Instead, the Mixed procedure in SAS® was employed to perform a Repeated Measures ANOVA with an assumed spatial powers covariance structure. The dependant variable was average speed and the independent variables were distance and distance^2. The distances were those 100-foot increments that had been used when calculating the average speed profiles. The Repeated Measures ANOVA with an assumed spatial powers covariance structure procedure is a form of linear regression which accounts for multiple observations of the same truck. It accounted for correlation between acceleration events for a given truck, so that two speed values at distances that were close to one another were more closely correlated than two speed values at distances that were far apart. Distance and distance^2 were included in the model because the truck speeds began to level off at large distances.

Models for 10th Percentile Speed

To create the models for the 10th percentile truck speeds, the bootstrap procedure in SAS® was used to predict 10th percentile truck speeds at distance intervals of 100 feet past the weigh station static scales. The procedure was to draw a random sample, with replacement, the same size as the number of observations in the data set. Then, the 10th percentile truck speed at each distance was calculated from the random sample. These steps were repeated 500 times to create the data set of 10th percentile bootstrap values. Using the 10th percentile bootstrap data set, the mean 10th percentile truck speed was then calculated at each distance. Finally, regression was performed on the mean 10th percentile truck speeds to generate the 10th percentile truck speed prediction equations.

Determining Cutoff Distance

A location was chosen within each data set past which the data were not used in the development of the mathematical model, so the models would not be based on too few observations. To do this, the resultant truck speed data from the average speed profile analyses for both the full data sets and the unimpeded truck data sets at the Alma, Hope, Joplin, and Lehi data collection sites were copied into a new spreadsheet. The data from the Marion data collection site were not needed because the data cutoff point was predetermined at 2600 feet due to the change in roadway grade from level to uphill.

By using the average speed values for each 100 foot increment, the change in average speed and then the rate of change in average speed were calculated. The cutoff point for each data collection site was chosen based on the distance where the rate of change in average speed became obviously larger than throughout the preceding data, indicating growing instability in the data. For the data sets that contained all of the truck acceleration events, the Alma cutoff point was located at 3200 feet, the Hope cutoff point was located at 2900 feet, the Joplin cutoff point was located at 4200 feet, and the Lehi cutoff point was located at 3900 feet past the weigh station static truck weight scales. For the data sets that contained only the unimpeded truck acceleration events, the Alma cutoff point was located at 3400 feet, the Hope cutoff point was located at 2700 feet, the Joplin cutoff point was located at 4200 feet, and the Lehi cutoff point was located at 4000 feet past the weigh station static truck weight scales.

Initial Speed Prediction Models

Once the Repeated Measures ANOVAs and the bootstrap procedures had been performed, graphs were developed that displayed the data used in each model, the truck speeds predicted by the model, and the 90% confidence intervals for the predicted truck speeds. To make the examination of the models easier, the average truck speed model graphs and the 10th percentile truck speed model graphs for each combination of site grade and acceleration event data set were combined. These graphs are shown in Figure 5-18 through Figure 5-23. For each of the three site grade classifications, the truck speed models created using all of the truck acceleration events are presented first, followed by the truck speed models created using only the unimpeded truck acceleration events.

Discussion of the Initial Speed Prediction Models

From Figures 5-18 and 5-19, it was noted that the “downhill” data produced models that showed the least signs of being asymptotic. This was expected because “downhill” roadway grades make acceleration easier for tractor-trailer trucks. The average and 10th percentile truck speed models in both figures have a significantly positive slope at the end of the data which indicates continued acceleration. While both of the 10th percentile truck speed models match the shape of the average truck speed models, the one developed using only unimpeded truck acceleration events matches more closely than the one developed using all of the truck acceleration events.

From Figures 5-20 and 5-21, which are the truck speed model graphs developed using the “level” data set, it was noted that the slope of the average truck speed line became negative towards the end of the data for both the all truck and unimpeded truck acceleration event data sets. Also, the 10th percentile truck speed lines became asymptotic at the end of each data set.

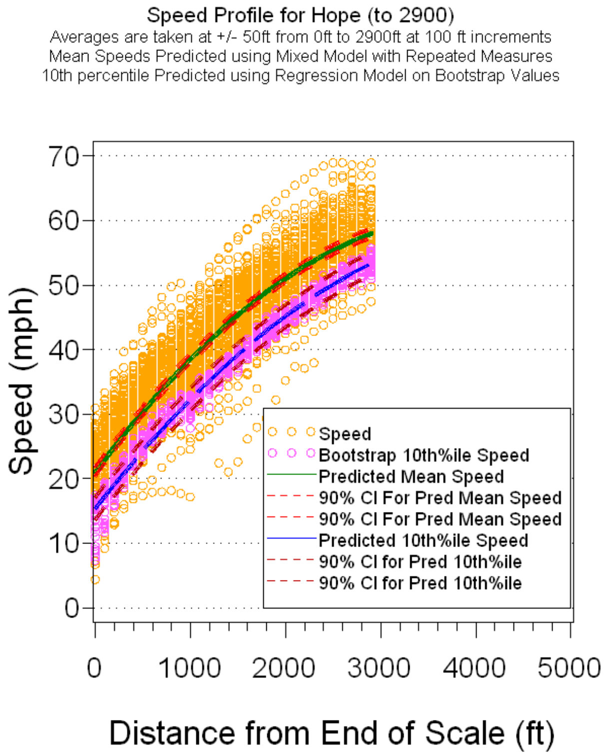

Figure 5-18: Truck Speed Models for “Downhill” All Data Set

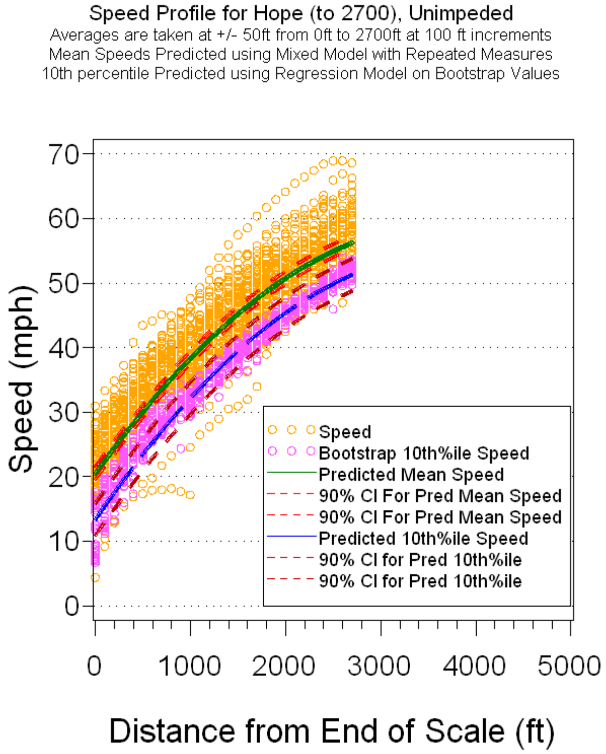

Figure 5-19: Truck Speed Models for “Downhill” Unimpeded Data Set

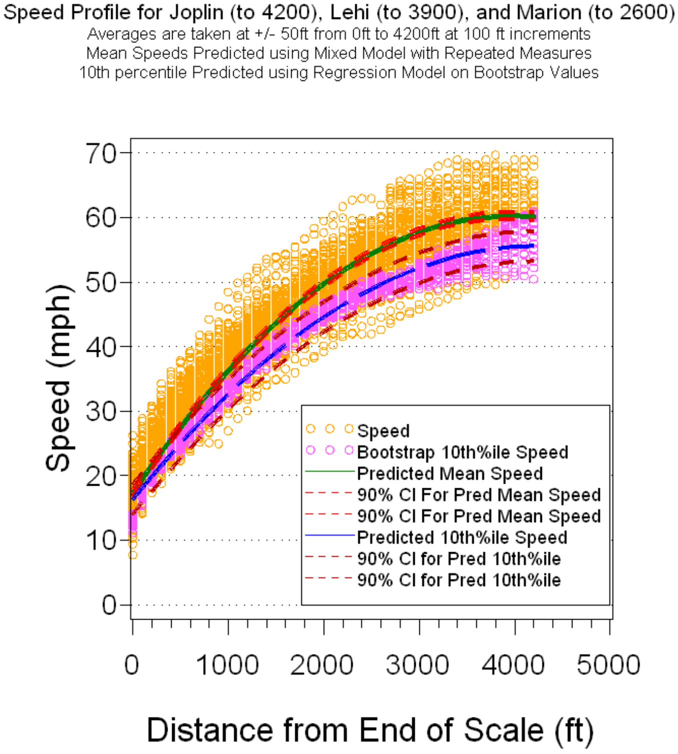
Speed Profile for Joplin (to 4200), Lehi (to 3900), and Marion (to 2600)
Averages are taken at +/- 50ft from 0ft to 4200ft at 100 ft increments
Mean Speeds Predicted using Mixed Model with Repeated Measures
10th percentile Predicted using Regression Model on Bootstrap Values

Figure 5-20: Truck Speed Models for “Level” All Data Set

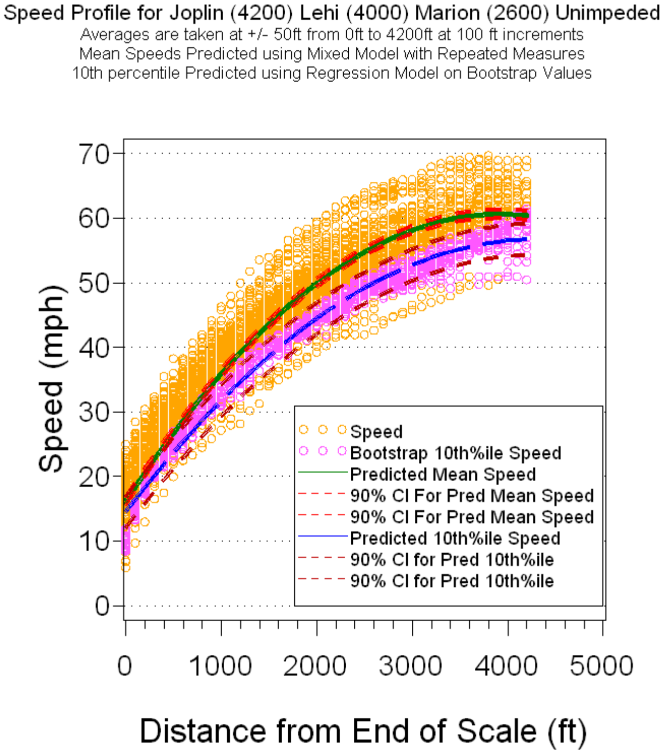
Speed Profile for Joplin (4200) Lehi (4000) Marion (2600) Unimpeded
Averages are taken at +/- 50ft from 0ft to 4200ft at 100 ft increments
Mean Speeds Predicted using Mixed Model with Repeated Measures
10th percentile Predicted using Regression Model on Bootstrap Values

Figure 5-21: Truck Speed Models for “Level” Unimpeded Data Set

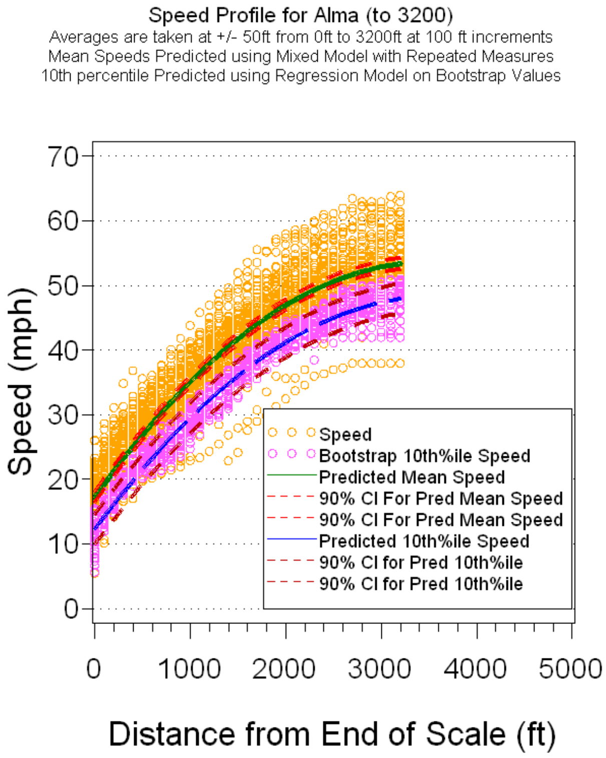

Figure 5-22: Truck Speed Models for “Uphill” All Data Set

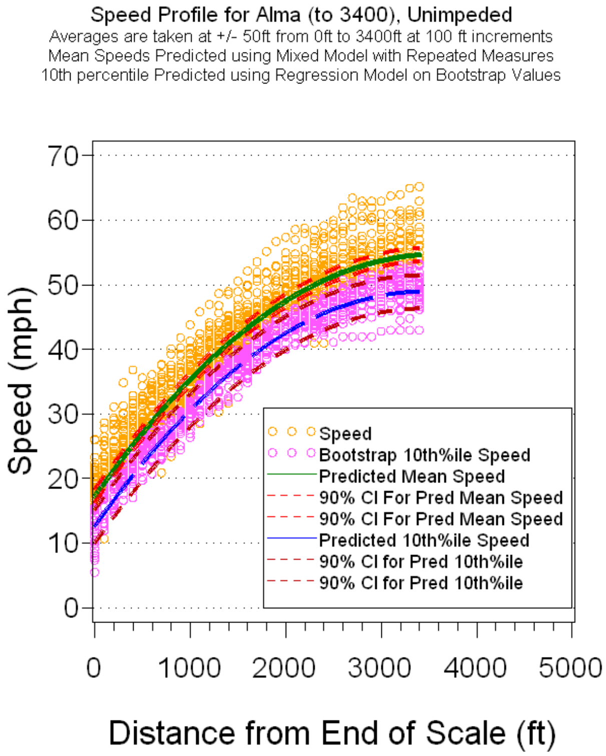

Figure 5-23: Truck Speed Models for “Uphill” Unimpeded Data Set

These attributes are not representative of the trucks' actual behavior, and it was suspected that the shapes of the models were being overly influenced by the large number of data points at the beginning of the data set. Another attribute noted from Figures 5-20 and 5-21 was that the average and 10th percentile truck speed lines for the "level" graphs begin closer together than those of the "downhill" and "uphill" graphs. The average and 10th percentile truck speeds from the unimpeded truck data set started out lower than those from the data set that included all of the trucks, but the truck speeds at the end of the profiles for the two graphs are almost the same. In Figure 5-21, which is for the unimpeded truck acceleration events, the negative slope of the average truck speed line was steeper than the negative slope of the average truck speed line created using all of the truck acceleration events.

From Figures 5-22 and 5-23, it was noted that the "uphill" data produced models that became asymptotic at the end of the data. This was expected because "uphill" roadway grades make acceleration harder for tractor-trailer trucks. However, the "uphill" models became asymptotic earlier than expected, resulting in an extremely large distance for both all and unimpeded average tractor-trailer trucks to accelerate to the freeway truck speed limit.

There are several factors that may have influenced the properties of the models and may have caused the asymptotic behavior of the model equations. The low acceleration at higher speeds may reflect decreased performance at higher speeds. Another factor that may have contributed to the asymptotic nature of the models could be the fit of models to the data. Increasing the order of the models may have resulted in a better fit through the range of much of the data, but could also create an unrepresentative hook shape at the upper end of the range.

Revised Speed Prediction Models

In an attempt to correct the problems with the truck speed models, it was decided to eliminate a section of data from the beginning of each data set and then develop additional models. Data up to a distance of 1000 feet past the weigh station static scales were eliminated from the data sets, the models were redeveloped, and the revised truck speed model graphs are in Figure 5-24 through Figure 5-29.

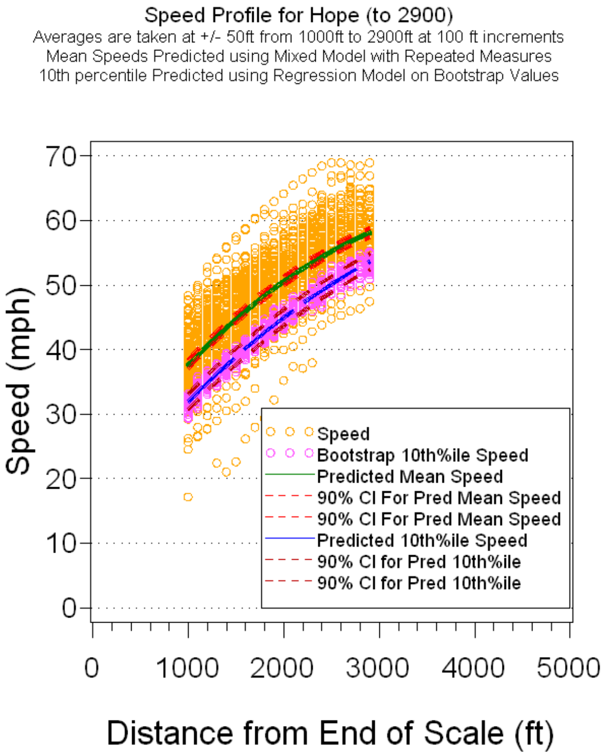

Figure 5-24: Revised Truck Speed Models-“Downhill” All Data Set

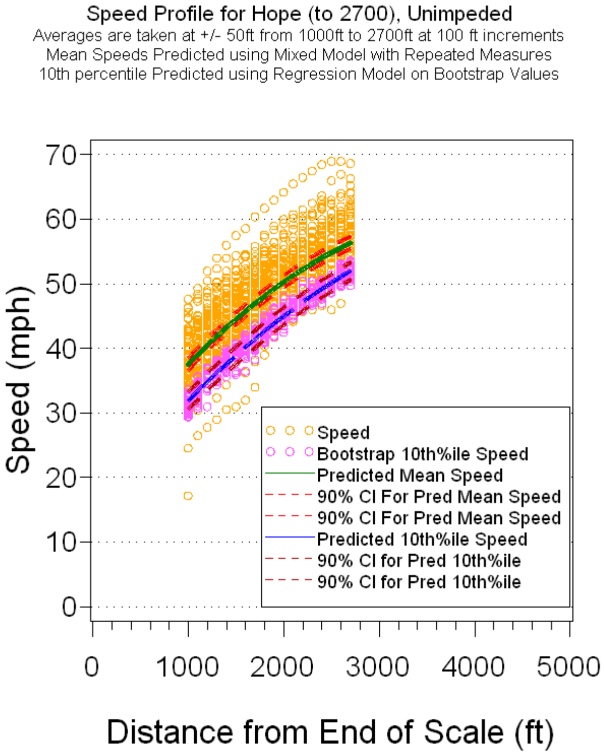

Figure 5-25: Revised Truck Speed Models-“Downhill” Unimpeded Data Set

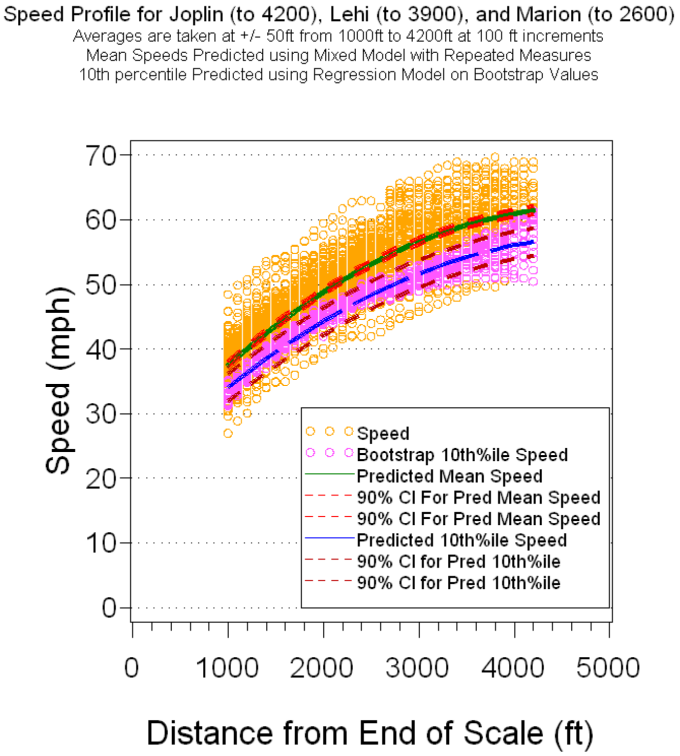

Figure 5-26: Revised Truck Speed Models-“Level” All Data Set

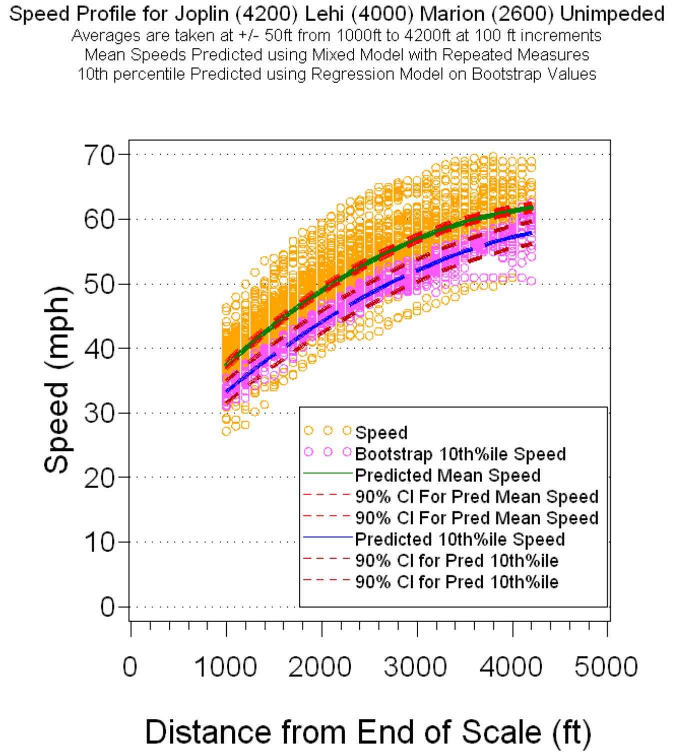

Figure 5-27: Revised Truck Speed Models-“Level” Unimpeded Data Set

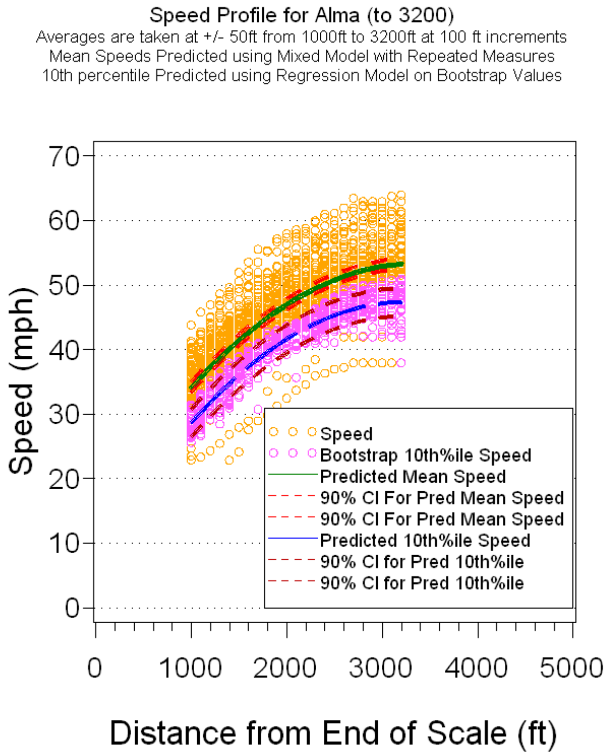

Figure 5-28: Revised Truck Speed Models-“Uphill” All Data Set

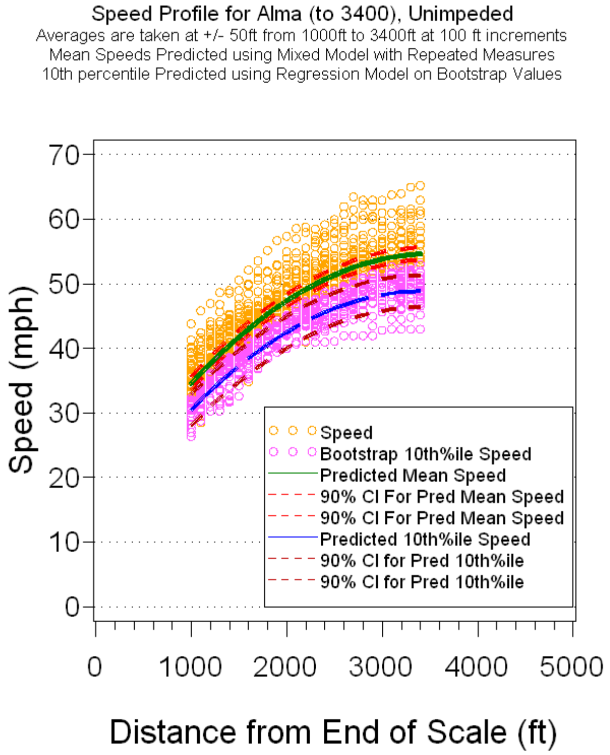

Figure 5-29: Revised Truck Speed Models-“Uphill” Unimpeded Data Set

Figures 5-24 through 5-29 show that excluding data from the beginning of each data set helped to correct some of the problems exhibited by the initial truck speed models.

The revised “downhill” models appeared to exhibit the least amount of change among the three site grade classifications. Only minor differences in the curvature of the model lines and the slope of the line at the end of the data are noticeable. The revised “downhill” models which began at 1000 feet past the static scales had slightly less curvature than the initial models and ended with slightly steeper slopes.

The revised “level” models showed that the exclusion of data from the models corrected the misrepresentative negative slopes that were present at the end of the models. The revised “level” models which began at 1000 feet past the static scales had less curvature than the initial models and maintained positive slopes throughout the range of the data.

The revised “uphill” models were not greatly affected by the exclusion of the data, and the asymptotic behavior of the models was not corrected by the data exclusion. It was noted from these revised “uphill” models that the average and 10th percentile truck speed models developed using all of the truck acceleration events showed signs that the exclusion of data had actually caused the asymptotic behavior of the models to become worse.

Table 5-10 and Table 5-11 display all of the coefficients from the model equations used to construct the previously presented truck speed prediction model graphs. To determine the predicted truck speed using these coefficients, the user must input the values in the tables into the following equation:

truck speed = y-axis intercept + distance*(first order term) + distance^2*(second order term).

To examine the effects that the data exclusion had on the truck speed models more closely, the model coefficients were used to calculate predicted average and 10th percentile truck speeds. Table 5-12 was constructed to compare the truck speeds predicted by the models at several distances past the weigh station static scales.

Table 5-10: Average and 10th Percentile Truck Speed Model Coefficients for All and Unimpeded Truck Acceleration Event Models Beginning at 0 Feet Past Static Scales

	truck speed model	y-axis intercept	first order(x)	second order(x^2)
“downhill” all data	average	21.0337	0.0200	$-2.50*10^{-6}$
	10th percentile	15.3950	0.0189	$-2.01*10^{-6}$
“downhill” unimpeded	average	20.4545	0.0206	$-2.73*10^{-6}$
	10th percentile	13.3221	0.0217	$-2.83*10^{-6}$
“level” all data	average	17.3881	0.0216	$-2.73*10^{-6}$
	10th percentile	16.3419	0.0185	$-2.18*10^{-6}$
“level” unimpeded	average	16.1577	0.0226	$-2.88*10^{-6}$
	10th percentile	14.4975	0.0195	$-2.24*10^{-6}$
“uphill” all data	average	17.2398	0.0208	$-2.97*10^{-6}$
	10th percentile	12.2669	0.0200	$-2.76*10^{-6}$
“uphill” unimpeded	average	17.2545	0.0210	$-2.95*10^{-6}$
	10th percentile	12.5832	0.0211	$-3.06*10^{-6}$

Table 5-11: Average and 10th Percentile Truck Speed Model Coefficients for All and Unimpeded Truck Acceleration Event Models Beginning at 1000 Feet Past Static Scales

	truck speed model	y-axis intercept	first order(x)	second order(x^2)
“downhill” all data	average	20.1187	0.0200	$-2.37*10^{-6}$
	10th percentile	15.2327	0.0185	$-1.83*10^{-6}$
“downhill” unimpeded	average	19.8869	0.0201	$-2.44*10^{-6}$
	10th percentile	15.1563	0.0186	$-1.84*10^{-6}$
“level” all data	average	22.8188	0.0165	$-1.73*10^{-6}$
	10th percentile	20.8749	0.0146	$-1.46*10^{-6}$
“level” unimpeded	average	22.2720	0.0169	$-1.80*10^{-6}$
	10th percentile	19.6650	0.0151	$-1.41*10^{-6}$
“uphill” all data	average	14.5263	0.0231	$-3.42*10^{-6}$
	10th percentile	8.1344	0.0243	$-3.76*10^{-6}$
“uphill” unimpeded	average	15.4647	0.0223	$-3.17*10^{-6}$
	10th percentile	12.2413	0.0214	$-3.12*10^{-6}$

Table 5-12: Predicted Average and 10th Percentile Truck Speeds from All Truck speed Models

	truck speed model beginning at (x)	predicted truck speed at					
		1000	1500	2000	2500	3000	3500
“downhill” all data	average(0)	38.5	45.4	51.0	55.4		
	average(1000)	37.8	44.8	50.6	55.3		
	10th percentile(0)	32.3	39.2	45.2	50.1		
	10th percentile(1000)	31.9	38.9	44.9	50.1		
“downhill” unimpeded	average(0)	38.3	45.2	50.7	54.9		
	average(1000)	37.6	44.6	50.3	54.9		
	10th percentile(0)	32.2	39.5	45.4	49.9		
	10th percentile(1000)	31.9	38.9	45.0	50.2		
“level” all data	average(0)	36.3	43.7	49.7	54.3	57.6	59.6
	average(1000)	37.6	43.7	48.9	53.3	56.8	59.4
	10th percentile(0)	32.7	39.2	44.6	49.0	52.2	54.4
	10th percentile(1000)	34.0	39.5	44.2	48.3	51.5	54.1
“level” unimpeded	average(0)	**35.9**	43.6	49.8	**54.7**	58.0	60.0
	average(1000)	**37.4**	43.6	48.9	**53.3**	56.8	59.4
	10th percentile(0)	**31.8**	**38.7**	44.5	49.3	52.8	55.3
	10th percentile(1000)	**33.4**	**39.1**	44.2	48.6	52.3	55.2
“uphill” all data	average(0)	35.1	41.8	47.0	50.7	52.9	
	average(1000)	34.2	41.5	47.1	50.9	53.1	
	10th percentile(0)	29.5	36.1	41.2	45.0	47.4	
	10th percentile(1000)	28.7	36.1	41.7	45.4	47.2	
“uphill” unimpeded	average(0)	35.3	42.1	47.5	51.3	53.7	
	average(1000)	34.6	41.8	47.4	51.4	53.8	
	10th percentile(0)	30.6	37.4	42.5	46.2	48.3	
	10th percentile(1000)	30.5	37.3	42.6	46.2	48.4	

The predicted speeds from models with and the models without data from the first 1000 feet past the ends of the weigh scales were fairly similar. The differences between the predicted truck speeds from the two models at these distances ranged from no difference to less than 2 mph. In general, the models that excluded the first 1000 feet predicted slightly lower speeds, and showed more acceleration (i.e., less flattening) at the greater distances compared to the models with data from the first 1000 feet.

CHAPTER 6

SUMMARY AND RECOMMENDATIONS

The objective of this research project was to examine the speeds reached at certain distances by trucks accelerating onto the main lanes of a freeway, and offers recommendations about the lengths of acceleration lanes needed for heavy vehicles to accelerate to speeds closer to the speeds on the main lanes. This would reduce the degree to which entering trucks disrupt freeway traffic flow as they merge into the main lanes. This would be applicable to locations such as commercial vehicle weigh stations and freeway interchanges near truck stops or industrial facilities.

Data were collected at four separate commercial vehicle weigh stations in Arkansas and one in southwest Missouri. The data for this project were collected using weigh-in-motion systems, static scales, video cameras, and lidar guns. This equipment provided speed and distance data that were correlated to the weight of each measured truck. The weights of the majority of the tractor-trailer trucks measured during this research project ranged from 40,000 to 80,000 pounds. Near the locations where data were collected during this project, the percentage of trucks present in the freeway traffic flow ranged from 14% near the Alma weigh station to 52% near the Hope weigh station. These percentages were based on traffic counts performed by the Arkansas Highway and Transportation Department in 2006 and the Missouri Department of Transportation in 2007.

The data for this project were analyzed using both graphical and statistical techniques including data distribution graphs and statistical significance tests. The effects that truck weight, freeway volume, and roadway grade had on the speeds of measured truck were examined and compared among the data collection sites. From the data, mathematical models that predicted the average and 10th percentile speeds for tractor-trailer trucks at each of three grade-groups (slight downgrade, nearly level, slight upgrade) were developed.

Table 6-1 compares the acceleration lane lengths recommended in the sources mentioned in the literature review with the models from this research project. The proposed acceleration lane lengths that were calculated using the research project model were developed using the revised unimpeded average truck speed model from the “level” site grade group. The acceleration lane lengths proposed by Deen, NCHRP Report 505, and the model developed during this research are substantially longer than those proposed by both the AASHTO Green Book and Fitzpatrick and Zimmerman. Note that both the AASHTO and the Fitzpatrick and Zimmerman values were based on passenger cars, not heavy trucks.

Table 6-1: Acceleration Lane Lengths from Reviewed Sources and Proposed Acceleration Lane Lengths from Research Project

		Deen 1957	AASHTO Green Book 2004	NCHRP Rept. 505 2003	Fitzpatrick and Zimmerman 2006	This study 2008
assumed initial speed (mph)		22	22	22	20	17
distance (ft) to reach	39 mph	-	550	850	-	-
	40 mph	1530	-	-	908	1203
	50 mph	-	1020	2230	1383	2119
	55 mph	-	1580	3260	1653	2731
	60 mph	-	-	-	1945	3655

NOTES:
1. Deen distances stated for semi-trailer trucks
2. AASHTO 2004 distances are not specifically for trucks; are similar to 1965 distances stated for passenger cars
3. NCHRP 505 distances are for a 180 lb/hp truck on a 0% grade
4. Fitzpatrick and Zimmerman distances are for passenger cars. The values listed in each row of this table for Fitzpatrick and Zimmerman are their values for a design speed that is 10 mph above the speed in the row in this table.
5. 2008 distances were calculated with the revised “level” unimpeded average truck speed model

While discussing the role of large trucks in the operation of highways, the 2004 Green Book states that a 10 mph reduction in truck speed should be used as the general guide for determining critical lengths of grade (AASHTO 2004). This recommendation was based on data that showed a dramatic increase in vehicular accidents when the speed differential between large trucks and passenger vehicles increased from 10 mph to 15 mph (AASHTO 2004). The same principle applies to tractor-trailer trucks entering a freeway via an acceleration lane. The greater the difference in speed between tractor-trailer trucks merging onto the freeway and vehicles on the freeway main lanes, the greater the potential for collisions. This research has shown that these large speed differentials exist. To reduce the magnitude of these speed differentials, longer acceleration lanes are needed so that the majority of tractor-trailer trucks can accelerate and enter the flow of traffic on the freeway at a speed closer to that of the main lanes.

Based on data from this research, when a high percentage of tractor-trailer trucks are entering the traffic flow on a freeway with a speed limit of 65 mph, an acceleration lane length on the order of 2700 feet is required just to allow an average vehicle on a level grade to get within 10 mph of the posted speed before the entry ramp ends. A length of almost 3500 feet would be needed to accommodate the 10th percentile vehicle. These acceleration lane lengths are of the same order of magnitude as those found in NCHRP Report 505. This suggests that acceleration lanes with lengths approximately equal to the values proposed by this project be considered at locations where significant volumes of trucks enter a freeway.

The data collected during this research project reflect actual tractor-trailer truck behavior. However, the scope of the project limited the number of sites that could be studied. This project did not consider all of the factors that influence the operations of tractor-trailer trucks on freeway entrance ramps, such as a wide range of roadway grades, sight distance limitations, ramp curvature, and ramp entrance control. Therefore, it is recommended that additional research be conducted to further examine the interactions between passenger vehicles and tractor-trailer trucks on freeways, as well as, the performance characteristics of tractor-trailer trucks.

Data from the Alma site showed that even with an upgrade of less than 1% for the first 2000 feet, speeds were about 2 mph less than those at the nearly level sites. As the Alma grade increased past the 2000 foot mark, the differences between the Alma speeds and the nearly-level speeds grew larger. This suggests that it is undesirable to locate commercial vehicle weigh stations at places where the re-entry ramps would be on an upgrade of more than about +0.1% or +0.2% for 3000 feet or more.

The findings also argue against raising speed limits on four lane freeways where heavy volumes of trucks enter the freeway on short entry ramps. Raising the speed limit will just increase the speed differential between traffic on the main lanes and the stream of entering trucks. This will result in more conflicts and congestion if the volume of entering trucks is such that it forces main lane traffic to divert to and overload the inside lane.

One significant question is unanswered. If drivers of heavy vehicles were provided the longer acceleration lanes, would they make use of them and accelerate to speeds near those of the main lanes before merging? To gain insight into this, a test site would have to be constructed. A trial installation at a site with a level or downhill entry ramp back onto the freeway, such as the current Lehi eastbound weigh station on I-40, could be considered for such a test. Not only does this site have level terrain, it also experiences heavy main lane volumes. Improved truck re-entry characteristics could improve the flow of traffic at this location. Designers should consider extending the entry ramp parallel to the main lanes for a considerable distance before having a paved neutral area. The width of the separation should be at least the width of the outside shoulder on the main lanes.

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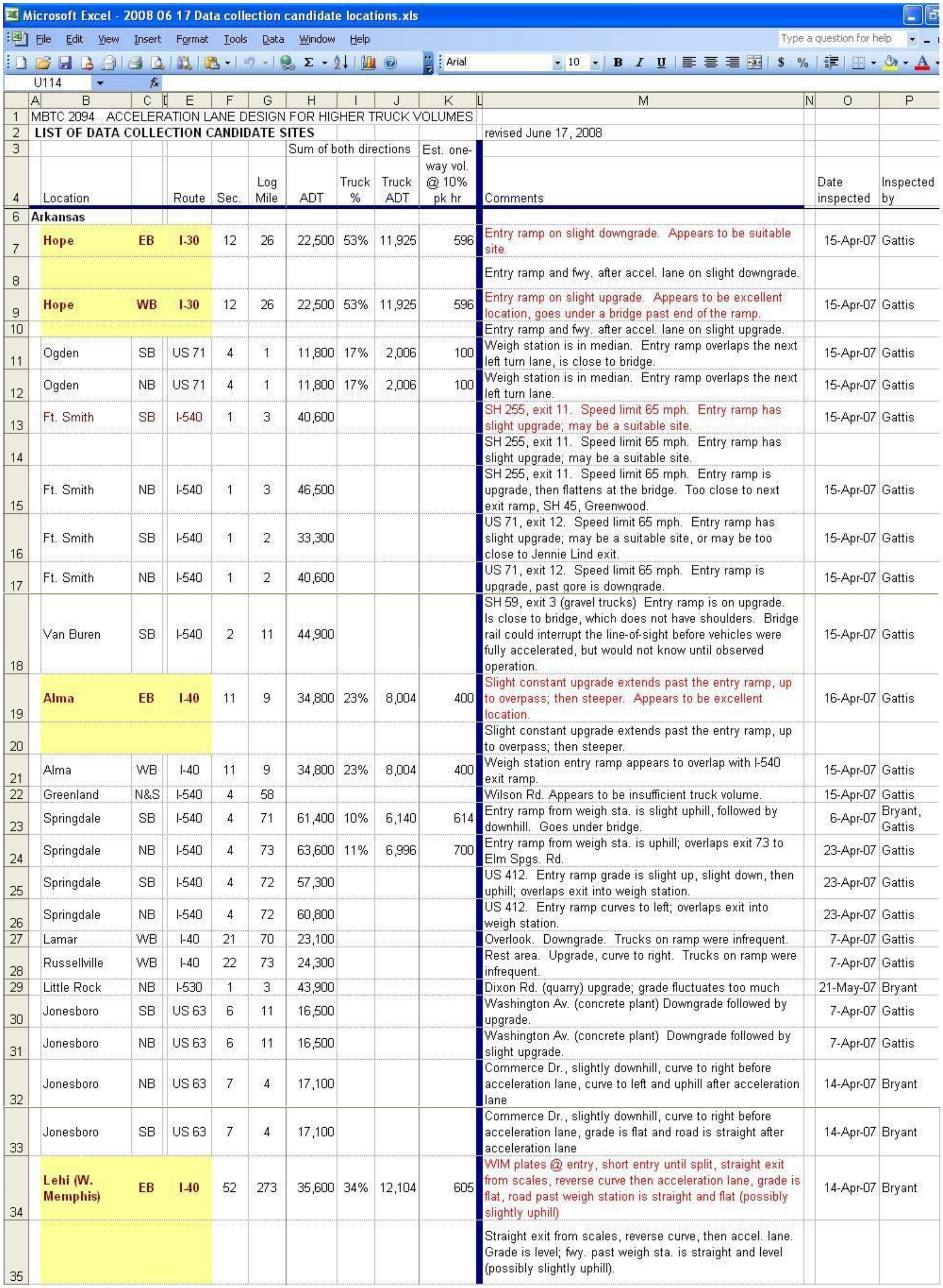
APPENDIX A: DATA COLLECTION CANDIDATE SITE LOCATION LIST



	A–B	C	E	F	G	H	I	J	K	M	O	P
1	MBTC 2094 ACCELERATION LANE DESIGN FOR HIGHER TRUCK VOLUMES											
2	**LIST OF DATA COLLECTION CANDIDATE SITES**									revised June 17, 2008		
3						Sum of both directions			Est. one-way vol. @ 10% pk hr			
4	Location		Route	Sec.	Log Mile	ADT	Truck %	Truck ADT		Comments	Date inspected	Inspected by
6	**Arkansas**											
7	**Hope**	**EB**	**I-30**	12	26	22,500	53%	11,925	596	Entry ramp on slight downgrade. Appears to be suitable site.	15-Apr-07	Gattis
8										Entry ramp and fwy. after accel. lane on slight downgrade.		
9	**Hope**	**WB**	**I-30**	12	26	22,500	53%	11,925	596	Entry ramp on slight upgrade. Appears to be excellent location, goes under a bridge past end of the ramp.	15-Apr-07	Gattis
10										Entry ramp and fwy. after accel. lane on slight upgrade.		
11	Ogden	SB	US 71	4	1	11,800	17%	2,006	100	Weigh station is in median. Entry ramp overlaps the next left turn lane, is close to bridge.	15-Apr-07	Gattis
12	Ogden	NB	US 71	4	1	11,800	17%	2,006	100	Weigh station is in median. Entry ramp overlaps the next left turn lane.	15-Apr-07	Gattis
13	Ft. Smith	SB	I-540	1	3	40,600				SH 255, exit 11. Speed limit 65 mph. Entry ramp has slight upgrade; may be a suitable site.	15-Apr-07	Gattis
14										SH 255, exit 11. Speed limit 65 mph. Entry ramp has slight upgrade; may be a suitable site.		
15	Ft. Smith	NB	I-540	1	3	46,500				SH 255, exit 11. Speed limit 65 mph. Entry ramp is upgrade, then flattens at the bridge. Too close to next exit ramp, SH 45, Greenwood.	15-Apr-07	Gattis
16	Ft. Smith	SB	I-540	1	2	33,300				US 71, exit 12. Speed limit 65 mph. Entry ramp has slight upgrade; may be a suitable site, or may be too close to Jennie Lind exit.	15-Apr-07	Gattis
17	Ft. Smith	NB	I-540	1	2	40,600				US 71, exit 12. Speed limit 65 mph. Entry ramp is upgrade, past gore is downgrade.	15-Apr-07	Gattis
18	Van Buren	SB	I-540	2	11	44,900				SH 59, exit 3 (gravel trucks) Entry ramp is on upgrade. Is close to bridge, which does not have shoulders. Bridge rail could interrupt the line-of-sight before vehicles were fully accelerated, but would not know until observed operation.	15-Apr-07	Gattis
19	**Alma**	**EB**	**I-40**	11	9	34,800	23%	8,004	400	Slight constant upgrade extends past the entry ramp, up to overpass; then steeper. Appears to be excellent location.	16-Apr-07	Gattis
20										Slight constant upgrade extends past the entry ramp, up to overpass; then steeper.		
21	Alma	WB	I-40	11	9	34,800	23%	8,004	400	Weigh station entry ramp appears to overlap with I-540 exit ramp.	15-Apr-07	Gattis
22	Greenland	N&S	I-540	4	58					Wilson Rd. Appears to be insufficient truck volume.	15-Apr-07	Gattis
23	Springdale	SB	I-540	4	71	61,400	10%	6,140	614	Entry ramp from weigh sta. is slight uphill, followed by downhill. Goes under bridge.	6-Apr-07	Bryant, Gattis
24	Springdale	NB	I-540	4	73	63,600	11%	6,996	700	Entry ramp from weigh sta. is uphill; overlaps exit 73 to Elm Spgs. Rd.	23-Apr-07	Gattis
25	Springdale	SB	I-540	4	72	57,300				US 412. Entry ramp grade is slight up, slight down, then uphill; overlaps exit into weigh station.	23-Apr-07	Gattis
26	Springdale	NB	I-540	4	72	60,800				US 412. Entry ramp curves to left; overlaps exit into weigh station.	23-Apr-07	Gattis
27	Lamar	WB	I-40	21	70	23,100				Overlook. Downgrade. Trucks on ramp were infrequent.	7-Apr-07	Gattis
28	Russellville	WB	I-40	22	73	24,300				Rest area. Upgrade, curve to right. Trucks on ramp were infrequent.	7-Apr-07	Gattis
29	Little Rock	NB	I-530	1	3	43,900				Dixon Rd. (quarry) upgrade; grade fluctuates too much	21-May-07	Bryant
30	Jonesboro	SB	US 63	6	11	16,500				Washington Av. (concrete plant) Downgrade followed by upgrade.	7-Apr-07	Gattis
31	Jonesboro	NB	US 63	6	11	16,500				Washington Av. (concrete plant) Downgrade followed by slight upgrade.	7-Apr-07	Gattis
32	Jonesboro	NB	US 63	7	4	17,100				Commerce Dr., slightly downhill, curve to right before acceleration lane, curve to left and uphill after acceleration lane	14-Apr-07	Bryant
33	Jonesboro	SB	US 63	7	4	17,100				Commerce Dr., slightly downhill, curve to right before acceleration lane, grade is flat and road is straight after acceleration lane	14-Apr-07	Bryant
34	**Lehi (W. Memphis)**	**EB**	**I-40**	52	273	35,600	34%	12,104	605	WIM plates @ entry, short entry until split, straight exit from scales, reverse curve then acceleration lane, grade is flat, road past weigh station is straight and flat (possibly slightly uphill)	14-Apr-07	Bryant
35										Straight exit from scales, reverse curve, then accel. lane. Grade is level; fwy. past weigh sta. is straight and level (possibly slightly uphill).		

36	Riverside (W. Memphis)	WB	I-40	52	283	35,600	34%	12,104	605	Exit from interstate slightly downhill at beginning, long deceleration lane before weigh station exit, WIM plates halfway down entry ramp, straight exit from scales, ramp angles to long acceleration lane, grade is flat through weigh station and acceleration lane, road is straight and uphill @ end of acceleration lane and after **Site under long term construction.**		14-Apr-07	Bryant
37	Bridgeport (W. Memphis)	NB	I-55	11	2	44,700	44%	19,668	983	Long straight entry ramp from interstate, WIM plates halfway down entry ramp, straight exit from scales, ramp angles to long acceleration lane, grade is flat through weigh station and acceleration lane, road is straight and flat after weigh station. May not be a place to observe downstream. May 28: ~ 0.4-0.5 mile past gore is flat, trucks were up to ~55 mph at begin of upgrade; downstream person may ? stand behind guardrail.		14-Apr-07	Bryant
38						Bridgeport hourly volumes are higher than at other sites; high volume interferes with tracking individual vehicles.						28-May-07	Gattis
39	Marion	SB	I-55	11	9	35,200	36%	12,672	634	WIM plates @ weigh station exit, straight exit from scales, long acceleration lane then reverse curve then acceleration lane for interstate, grade is flat through weigh station, road is straight after weigh station, road is uphill after acceleration lane **Has embankment for a downstream observer position. Level, then steep upgrade, unsure if trucks are fully accelerated before the upgrade.**		14-Apr-07	Bryant
40										Straight exit from scales, long lane, reverse curve, then accel. lane for fwy. Grade is flat through weigh station, fwy. is upgrade after accel. lane.			
41	Blytheville	SB	I-55	12	72	17,700	47%	8,319	416	Inspection station (old weigh station), short deceleration lane, angles to small scale, no WIM, straight exit from scale then reverse curve then short acceleration lane, grade is flat through inspection station, road is straight and flat after inspection station		14-Apr-07	Bryant
42													
43	**ADJACENT STATES**												
44													
45	**Missouri**												
46	Charleston	NB	I-57		18	10,560		4,209					
47	Charleston	SB	I-57		18	10,560		4,209					
48	Steele	NB	I-55			15,730							
49	Caruthersville	NB	I-155			7,808		2,886					
50	Joplin	EB	I-44		3	23,885		8,179				16-May-07	Bryant
51	**Joplin**	**WB**	**I-44**		3	23,885		8,179				16-May-07	Bryant
52	Harrisonville	N&S	US 71			31,983							
53	Mayview	E&W	I-70			27,268							
54	Platte City	NB	I-29		24	73,364							
55	Lone Jack	E&W	US 50			19,909							
56	Willow Springs	E&W	US 60			10,343		2,421					
57	Kearney	N&S	I-35		22	31,144							
58													
59	**Mississippi**												
60	Southhaven	N&S	I-55			48,000							
61	Olive Branch	E&W	US 78			29,000							
62													
63	**Tennessee**												
64	Brownsville	EB	I-40		50	35,980				may be ok		18-May-07	Gattis
65	Brownsville	WB	I-40		50	35,980				is level, then upgrade		18-May-07	Gattis
66	Greene County		I-81			32,600							
67	Knoxville	EB	I-40			101,760							
68	Knoxville	WB	I-40			101,760							
69	Coffee County		I-24			36,180							
70	Coffee County		I-24			36,180							
71	Robertson County		I-65			44,140							
72	Robertson County		I-65			44,140							
73													
74	**Oklahoma**												
75	Colbert	NB	US 75										
76	Colbert	SB	US 75										
77	El Reno	EB	I-40		122					short ramps			
78	El Reno	WB	I-40		122					short ramps			
79	Hugo	NB	US 271										
80	Hugo	SB	US 271										
81	Boise City	N&S	US 287							single scale for both directions, within city limits, has no ramps			
82	Blackwell	NB	I-35		218								
83	Blackwell	SB	I-35		218								
84	Davis	NB	I-35		53								
85	Davis	SB	I-35		53								
86	Woodward	N&S	US 270-412							single scale for both directions, within city limits, has no ramps			