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OPERATING SPEED MODELS FOR PASSENGER CARS AND TRUCKS ON HORIZONTAL CURVES WITH STEEP GRADES

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ABSTRACT

Past research suggests that operating speed profiles replace the design speed concept as the primary instrument when designing highways. This thesis builds upon this research by investigating the effect of alignment geometry and highway characterisitcs on passenger car and truck operating speeds. Continuous speed data were collected from 19 different multilane highway segments located in in Washington, California, West Virginia, Maryland, and Pennsylvania. All sites contained a tangent section with a steep grade (greater than 4 percent) that progresses into a sharp horizontal curve.

Mean speed prediction models were developed using an ordinary least squares (OLS) modeling approach. Separate models were developed for the approach tangent and the point of curvature (PC) of the horizontal curve. For passenger cars on the approach tangent, the significant factors are horizontal curve radius, approach tangent percent grade, posted speed limit, and superelevation on the horizontal curve. For passenger cars at the PC, the significant factors are horizontal curve radius, approach tangent percent grade, posted speed limit, the presence of an advisory speed sign, lane width, and superelevation on the horizontal curve. For trucks on both the approach tangent and at the PC, the significant factors are horizontal curve radius, approach tangent percent grade, posted speed limit for trucks, the presence of an advisory speed sign, and lane width.

A three-stage least squares (3SLS) modeling approach was used to investigate the possible endogeneity of passenger car speed and truck speed in the system of equations and to account for the contemporaneous correlation between the disturbances across the equations. The results indicate that endogeneity may exist between passenger car and

truck speeds. Thus, it is recommended that future multilane highway speed models consider using simultaneous equations to account for the endogenous relationship between passenger cars and trucks.

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Chapter 1. INTRODUCTION

Design consistency is the matching of roadway features with the expectation of drivers. It should be considered as part of highway design. The American Association of State Highway and Transportation Officials' (AASHTO) *A Policy on Geometric Design of Highways and Streets* (herein referred to as the Green Book) uses the design speed concept to establish geometric design controls and criteria for roadway sections (AASHTO 2004). The intent is to apply design criteria so that alignments meet driver expectations. This would then allow vehicle speeds to be consistent through the extent of the roadway segment. The design speed concept operates under the assumption that all vehicles will travel at or below the design speed (Krammes et al. 1994). However, this assumption does not hold true for all roadways. It has been suggested that operating speed profiles replace the design speed concept in the design of roadway alignments (Leisch and Leisch 1977).

Developing operating speed models is the first step toward determining the factors that are associated with driver speed choice. A large body of operating speed modeling literature exists; however, only a few of these models are applicable to multilane highways. One objective of this thesis will be to supplement the two-lane rural highway operating speed models with additional multilane highway models.

Research has shown that truck operating speeds are lower than passenger car speeds on open highways (Leisch and Leisch 1977). This is exaggerated on vertical gradients, where truck operating speeds are determined primarily by the mechanical characteristics of the vehicle. The speed differential between passenger cars and trucks causes inconsistent vehicle operations on vertical grades. Thus, understanding the operating speeds of trucks is essential to the design consistency of roadway segments containing steep grades. There is a need for further research on the development of operating speed profiles of large trucks (Donnell et al. 2001; Harwood et al. 2003). There is also no research completed on the development of operating speed models of large trucks using only field data. Therefore, a second objective of this thesis will be to develop operating speed models of large trucks on steep grades. The truck operating speed models will be compared to the passenger car operating speed models to enhance the existing body of literature on the relationship between driver speed choice and geometric design features.

Chapter 2. LITERATURE REVIEW

This section will review the published literature that is pertinent to this thesis. It was determined that the two major categories of previous research that would be most supportive in providing established relationships between speeds and geometric features were for trucks and for multilane highways. Therefore, the previous research presented in this section contains speed modeling in which trucks were the main study vehicle, or the study included multi-lane highways in the site selection criteria, regardless of vehicle type.

Speed Prediction Models for Trucks

Leisch and Leisch (1977) studied the operating speeds of cars and trucks to develop a new concept in design consistency. Speed profile models were developed with respect to both horizontal and vertical alignments, and were based on the following assumptions:

- Low volumes;
- Average traffic speeds;
- Favorable roadway conditions;
- Separate average operating speeds for trucks, which travel 5 mph slower than passenger cars on average;
- Trucks having an average weight to power ratio of 200;
- Deceleration and acceleration rates based on AASHO and FHWA standards.

It was determined that truck speeds primarily depend on the mechanical properties of the truck, which is based on its weight-to-horsepower ratio. Passenger car speeds, however, primarily depend on driver comfort characteristics on horizontal curves. Therefore, the speed profile models for cars were based on horizontal alignments and the speed profile models for trucks were based on both horizontal and vertical alignments. It was concluded that the speed differential between the two models could be directly used to determine designs for certain highways. Figure 1 shows a practical application of this method for an alignment in which the passenger car and truck speeds vary greatly. The authors suggested that operating speeds between vehicle types should not vary by more than 10 mph.

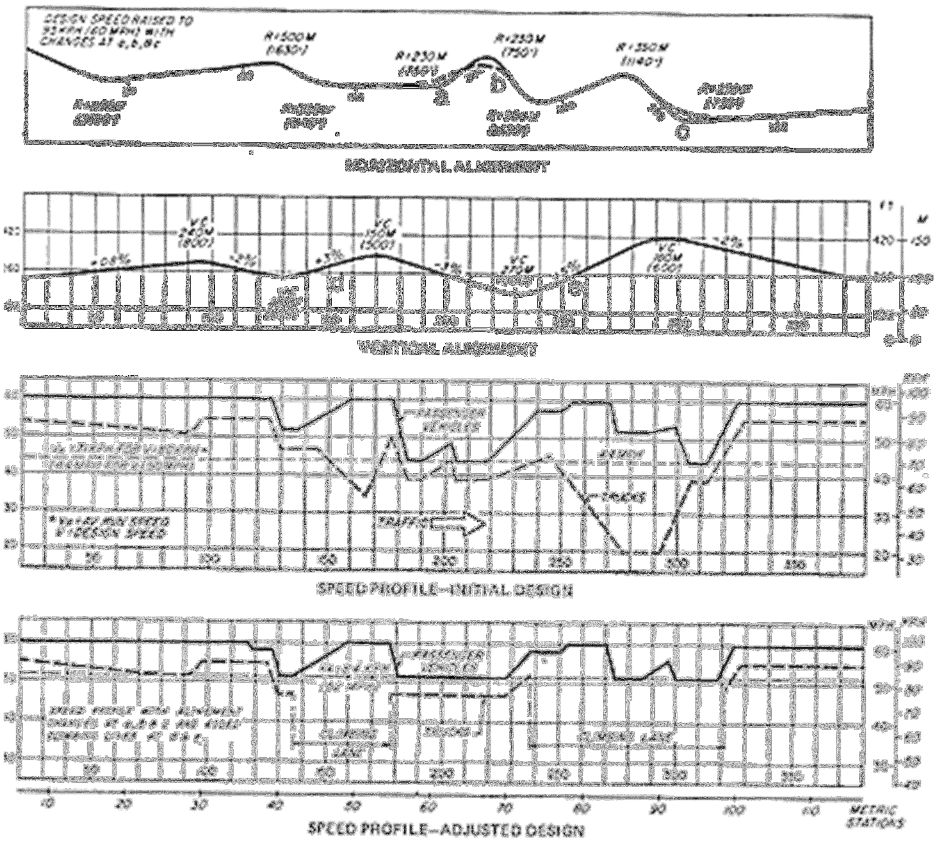
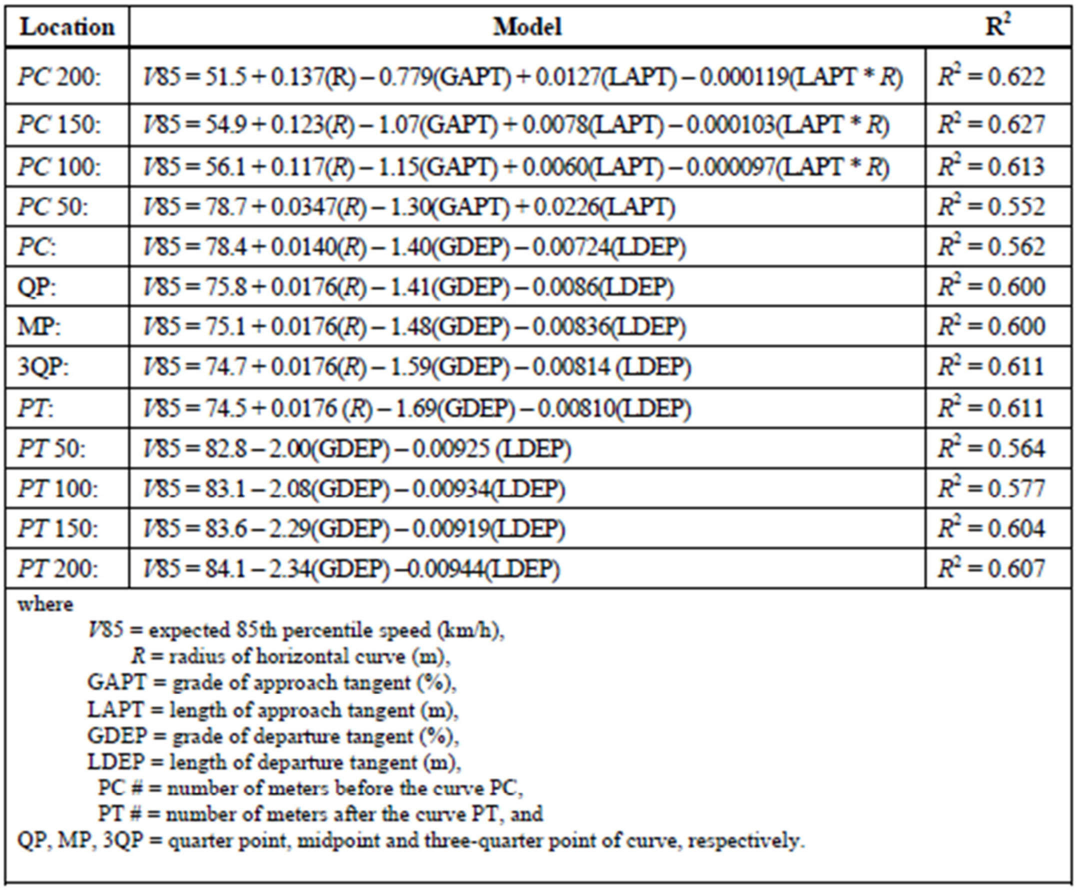


Figure 1 – Geometric Design Based on Design Consistency (Leisch and Leisch 1977)

Donnell et al. (2001) developed statistical models of operating speeds for cars and trucks on two-lane rural highways using data from 17 horizontal curves in Pennsylvania and Texas. Field data were combined with simulation data from the "Two-Lanes with Passing" (TWOPAS) software to create 85th percentile operating speed models for different locations along the curve. Table 1 shows the operating speed models for each of these points, as well as the direction and magnitude of the statistically significant predictor variables. Increasing the radius of curve and length of approach tangent is associated with an increase in truck speed along the approach tangent through the point of tangency (PT). An increase in the approach tangent length is also associated with an increase in truck speed along the approach tangent through the point of tangency (PT). An increase in approach grade was associated with a decrease in mean truck speed along the approach tangent to the PT. An increase in the grade of the departure tangent combined with an increase in the length of the departure tangent was associated with a decrease in mean truck speed from the PT through the departure tangent.



Location	Model	R^2
PC 200:	$V85 = 51.5 + 0.137(R) - 0.779(GAPT) + 0.0127(LAPT) - 0.000119(LAPT * R)$	$R^2 = 0.622$
PC 150:	$V85 = 54.9 + 0.123(R) - 1.07(GAPT) + 0.0078(LAPT) - 0.000103(LAPT * R)$	$R^2 = 0.627$
PC 100:	$V85 = 56.1 + 0.117(R) - 1.15(GAPT) + 0.0060(LAPT) - 0.000097(LAPT * R)$	$R^2 = 0.613$
PC 50:	$V85 = 78.7 + 0.0347(R) - 1.30(GAPT) + 0.0226(LAPT)$	$R^2 = 0.552$
PC:	$V85 = 78.4 + 0.0140(R) - 1.40(GDEP) - 0.00724(LDEP)$	$R^2 = 0.562$
QP:	$V85 = 75.8 + 0.0176(R) - 1.41(GDEP) - 0.0086(LDEP)$	$R^2 = 0.600$
MP:	$V85 = 75.1 + 0.0176(R) - 1.48(GDEP) - 0.00836(LDEP)$	$R^2 = 0.600$
3QP:	$V85 = 74.7 + 0.0176(R) - 1.59(GDEP) - 0.00814(LDEP)$	$R^2 = 0.611$
PT:	$V85 = 74.5 + 0.0176(R) - 1.69(GDEP) - 0.00810(LDEP)$	$R^2 = 0.611$
PT 50:	$V85 = 82.8 - 2.00(GDEP) - 0.00925(LDEP)$	$R^2 = 0.564$
PT 100:	$V85 = 83.1 - 2.08(GDEP) - 0.00934(LDEP)$	$R^2 = 0.577$
PT 150:	$V85 = 83.6 - 2.29(GDEP) - 0.00919(LDEP)$	$R^2 = 0.604$
PT 200:	$V85 = 84.1 - 2.34(GDEP) - 0.00944(LDEP)$	$R^2 = 0.607$

where
$V85$ = expected 85th percentile speed (km/h),
R = radius of horizontal curve (m),
GAPT = grade of approach tangent (%),
LAPT = length of approach tangent (m),
GDEP = grade of departure tangent (%),
LDEP = length of departure tangent (m),
PC # = number of meters before the curve PC,
PT # = number of meters after the curve PT, and
QP, MP, 3QP = quarter point, midpoint and three-quarter point of curve, respectively.

Table 1 – Truck Operating Speed Models (Donnell et al. 2001)

Adolini and Elefteriadou (2003) modeled the operating speed of trucks on two-lane rural highways. Data were used from Fitzpatrick et al. (1999), which included geometric design and speed data from 67 sites in Minnesota, New York, Pennsylvania, Oregon, Washington, and Texas. The data collected at these sites combined horizontal curvature with vertical curvature. TWOPAS simulation was used to estimate speed profile models for the mean truck speeds on different grades. Speeds were predicted for multiple points along horizontal curves, as well as at the beginning of the tangent and at the midpoint of the horizontal curve. The models that were developed are shown in Table 2.

Table 2 – Truck Operating Speed Models (Adolini and Elefteriadou 2003)

Models for 13 locations on grades 0% to 5%:		
- PC200	$V_{avg} = 107 - 8315/R$	$R^2 = 0.846$
- PC150	$V_{avg} = 103 - 7066/R$	$R^2 = 0.804$
- PC100	$V_{avg} = 103 - 7188/R$	$R^2 = 0.752$
- PC50	$V_{avg} = 95.8 - 4787/R$	$R^2 = 0.570$
- PC	$V_{avg} = 94.7 - 2028/R - 1.98\ G_1 - 0.0140\ T_1$	$R^2 = 0.568$
- QP	$V_{avg} = 95.6 - 3043/R - 1.79\ G_1 - 0.0110\ T_1$	$R^2 = 0.505$
- MP	$V_{avg} = 95.6 - 3017/R - 1.85\ G_1 - 0.0111\ T_1$	$R^2 = 0.522$
- 3QP	$V_{avg} = 96.1 - 4912/R$	$R^2 = 0.496$
- PT	$V_{avg} = 96.0 - 3016/R - 2.23\ G_1 - 0.0120\ T_1$	$R^2 = 0.552$
- PT50	$V_{avg} = 98.0 - 5876/R$	$R^2 = 0.895$
- PT100	$V_{avg} = 91.1 - 3439/R$	$R^2 = 0.793$
- PT150	$V_{avg} = 90.9 - 3381/R$	$R^2 = 0.772$
- PT200	$V_{avg} = 90.9 - 3375/R$	$R^2 = 0.772$
Models for 13 locations on grades –5% to 0:		
- PC200	$V_{avg} = 101 - 0.0277\ T1$	$R^2 = 0.783$
- PC150	$V_{avg} = 95.3 - 3457/R$	$R^2 = 0.947$
- PC100	$V_{avg} = 95.1 - 3412/R$	$R^2 = 0.514$
- PC50	$V_{avg} = 94.8 - 3167/R$	$R^2 = 0.669$
- PC	$V_{avg} = 95.1 - 3009/R + 1.27\ G_1$	$R^2 = 0.648$
- QP	$V_{avg} = 94.9 - 2741/R + 1.80\ G_1$	$R^2 = 0.700$
- MP	$V_{avg} = 94.7 - 2835/R + 1.64\ G_1$	$R^2 = 0.728$
- 3QP	$V_{avg} = 95.0 - 2876/R + 2.14\ G_1$	$R^2 = 0.726$
- PT	$V_{avg} = 94.4 - 2632/R + 2.11\ G_1$	$R^2 = 0.735$
- PT50	$V_{avg} = 96.2 - 3163/R + 3.12\ G_1$	$R^2 = 0.930$
- PT100	$V_{avg} = 96.0 - 3078/R + 3.16\ G_1$	$R^2 = 0.926$
- PT150	$V_{avg} = 95.9 - 3085/R + 3.05\ G_1$	$R^2 = 0.920$
- PT200	$V_{avg} = 96.0 - 3178/R + 2.82\ G_1$	$R^2 = 0.908$
Models for tangent and curve midpoint (MP):		
- Tangent 0 to 5%	$V_{avg} = 94.2 - 4088/R$	$R^2 = 0.822$
- MP, 0 to 5%	$V_{avg} = 93.1 - 4051/R$	$R^2 = 0.839$
- Tangent > 5%	$V_{avg} = 76.3 - 128\ e$	$R^2 = 0.263$
- MP > 5%	$V_{avg} = 95.9 - 1439/R - 3.81\ G1 - 0.0291\ T_1$	$R^2 = 0.626$
- Tangent ≤ 5%	$V_{avg} = 93.7 - 3266/R$	$R^2 = 0.788$
- MP ≤ 5%	$V_{avg} = 92.3 - 3157/R$	$R^2 = 0.966$
- Tangent –5% to 0	$V_{avg} = 99.7 - 4389/R + 1.71\ G_1$	$R^2 = 0.888$
- MP, –5% to 0	$V_{avg} = 95.3 - 4055/R$	$R^2 = 0.849$
Crest Vertical Curve on Horizontal Tangents (Tangent and Midpoint of VC)		
- Tangent	$V_{avg} = 98.2 - 0.299K - 1.03G_1 + 0.0260T_1$	$R^2 = 0.826$
- MP	$V_{avg} = 90.0 - 0.0354\ L_v + 0.0463\ \mathrm{T}_1$	$R^2 = 0.727$
Sag Vertical Curve on Horizontal Tangents		
- No significant models found. Use desired speed.		
Horizontal Curves Combined with Vertical Crest Curves		
- Tangent	$V_{avg} = 94.2 - 1248/R - 2.36\ G_1$	$R^2 = 0.774$
- MP	$V_{avg} = 93.9 - 2331/R - 1.54\ G_1$	$R^2 = 0.786$
Horizontal Curves Combined with Vertical Sag Curves		
- Tangent	$V_{avg} = 98.3 - 2385/R - 0.046\ L_v$	$R^2 = 0.749$
- MP	$V_{avg} = 94.6 - 3700/R + 111\ e - 0.0312\ L_v$	$R^2 = 0.895$

Where: V_{avg} = mean speed (km/h);
R = radius of curvature (m);
G_1 = approach tangent grade (%);
T_1 = approach tangent length (m);
e = superelevation rate;
K = L/A = length of vertical curve / algebraic change in grade (%);
L_v = length of vertical curve (m);
PC# = number of meters before the point of curvature;
PT# = number of meters after the point of tangency;
QP = quarter point of curve;
MP = midpoint of curve; and
3QP = three-quarter point of curve.

An increase in approach tangent length and approach tangent grade were associated with a decrease in mean truck speed for a few points between the point of curvature (PC) and PT. An increase in the length of vertical curve was associated with a decrease in mean truck speed.

Speed Prediction Models for Multilane Highways

Shankar and Mannering (1998) investigated the endogenous relationship between lane-mean speeds and lane-speed deviations on multilane highways. Speed data were collected on a six-lane highway for both directions at one site in Washington. The data were collected for all vehicles in 10 mph bins, aggregated over one hour. A three-stage least squares (3SLS) approach was used to develop models for lane mean speeds and lane-speed deviations. The study found that endogenous relationships exist among lane mean speeds and between lane mean speeds and speed deviations. In-lane speeds are affected by adjacent lane speeds, and in-lane speed deviations are affected by in-lane speeds, adjacent lane speeds and adjacent lane speed deviations. It was found that an increase in-lane traffic flow, an increase in adjacent lane mean speeds, and an increase in right lane truck flow were associated with increased mean speed in all lanes. An increase in truck percentage in the left lane was associated with an increase in left lane mean speed. An increase in hourly traffic flow in the middle lane was associated with a decrease in middle lane mean speed.

Dixon et al. (1999) studied the relationship between the posted speed limit and observed free-flow speeds after the national maximum speed limit was repealed in 1995. Speed data were collected prior to and following speed limit increases from 55 mph to 65 mph at 12 rural multilane sites in Georgia. Speed data were collected for all vehicles. A mean comparison test concluded that the higher posted speed limit resulted in statistically greater free-flow speeds. The author developed a model that predicts free-flow speeds (FFS), which is shown in Table 3. An increase in posted speed limit was associated with an increase in free-flow speed.

Source	**Speed Condition**	**Free-Flow Speed**	
		Metric (km/h)	**Imperial (mph)**
HCM and McShane et al. (1998)	85th-percentile ≥ 96.6 km/h (60 mph)	FFS = 85SP – 4.8	FFS = 85SP - 3
	Posted ≥ 88.6 km/h (55 mph)	FFS = SL + 8.1	FFS = SL + 5
Alternative rules-of-thumb per this study	85th-percentile ≥ 96.6 km/h (60 mph)	FFS = 85SP – 8.7	FFS = 85SP – 5.4
	Posted = 88.6 km/h (55 mph)	FFS = SL + 10.4	FFS = SL + 6.5
	Posted = 104.7 km/h (65 mph)	FFS = SL – 0.5	FFS = SL – 0.3

Note:
FFS Free-flow speed for ideal conditions, km/h (mph)
85SP 85th-percentile speed, km/h (mph)
SL Speed limit, km/h (mph)

Table 3 – Free Flow Speed Models (Dixon et al. 1999)

Tarris et al. (1996) compared various modeling techniques to predict operating speeds for low-speed, multilane urban streets. Passenger car free-flow operating speeds were collected along 27 urban collectors in Pennsylvania. Ordinary least squares (OLS) regression and a panel analysis approach were used to develop models to predict the effect of degree of curve on operating speeds. Different models were created for aggregate and individual speed data to illustrate how data aggregation affects model estimation. It was concluded that the use of aggregated data results in a reduction in speed variability and may over- or understate the influence of geometric elements on operating speeds. Also, the a panel modeling approach was shown to more adequately capture the individual driver and time effects on mean operating speed. The results for the panel analysis speed prediction model are shown in Table 4. All models developed by the authors resulted in degree of curve having a statistically significant negative association with mean passenger car operating speeds (i.e., increasing the degree of horizontal curve was associated with a reduction in the mean passenger car speed).

Regression Function (no group or time effects):

$$Y = 52.18 - 0.231D$$

Where:

Y = individual speed observation

D = degree of curvature

R^2, percent:

Group Effects (individual drivers) Only:	70.6
Degree of Curvature Only:	48.7
Degree of Curvature and Group:	79.2
Degree of Curvature, Group, and Time:	80.0

Table 4 – Speed Prediction Model (Tarris et al. 2006)

Fitzpatrick et al. (1997) studied the relationship between operating speed and design speed for four-lane roadways with divided cross-sections. Free-flow speeds were collected at 14 suburban sites with horizontal curves and 10 suburban sites with vertical curves in Texas. The data only included passenger cars, pickup trucks, and vans. Regression analysis was used to predict the 85th percentile speeds. The study showed that the 85th percentile speed could be predicted by curve radius for horizontal curves and by the design speed (related to vertical sight distance) for vertical curves for vehicles in the outside lane. The models developed by the authors are shown in Table 5. An increase in inferred design speed was associated with an increase in 85th percentile speed for horizontal and vertical curves. An increase in the inverse of access density was associated with an increase in 85th percentile speed for horizontal curves.

Horizontal Curve:

$V85_{tan} = 74.91 + 22.29/AD$ $R^2 = 0.71$

$V85_{curve} = 43.5 + 0.38(IDS)$ $R^2 = 0.83$

$V85_{curve} = 56.34 + 0.808R^{0.5} + 9.34/AD$

Vertical Curve:

$V85_{curve} = 39.51 + 0.556(IDS)$ $R^2 = 0.56$

Where:

$V85_{tan}$ = the 85th percentile approach tangent speed (km/h);
$V85_{curve}$ = 85th percentile curve speed (km/h);
AD = approach access density (number of access points per km);
IDS = inferred design speed (km/h); and
R = curve radius (m).

Table 5 – 85th Percentile Speed Models (Fitzpatrick 1997)

Poe and Mason (2000) evaluated the efficacy of a mixed-model statistical approach to analyze the influence of geometric features on operating speed. The data used in the study were collected by Tarris et al. (1996) at 27 sites on urban collectors in Pennsylvania for passenger cars. It was found that the mixed modeling approach provided an appropriate method for analyzing vehicle speed observations at multiple sites. Models were developed for mean speeds at the following locations: 150 feet before the point of curvature (PC), at the PC, at the midpoint of the curve, and at the PT. The mean speed (km/hr) models are shown in Table 6. An increase in degree of curve was associated with an increase in mean speed at all points. An increase in grade was associated with an increase in mean speed at all points. An increase in lane width was associated with an increase in mean speed 150 feet before the PC and at the PT, and a decrease in mean speed from the PC to the midpoint of the horizontal curve. An increase in the roadside hazard rating was associated with a decrease in mean speed from 150 feet before the PC to the midpoint at the curve, and an increase in mean speed at the PT.

PC150	$49.59 + 0.5(DEGCVR) - 0.35(GRADE) + 0.74(LNWIDN) - 0.74(HZRT5M)$
PC	$51.13 - 0.1(DEGCVR) - 0.24(GRADE) - 0.01(LNWIDN) - 0.57(HZRT5M)$
MID	$48.82 - 0.14(DEGCVR) - 0.75(GRADE) - 0.12(LNWIDN) - 0.12(HZRT5M)$
PT	$43.41 - 0.11(DEGCVR) - 0.12(GRADE) + 1.07(LNWIDN) + 0.30(HZRT5M)$

Where:
$DEGCVR$ = degree of curve
$GRADE$ = approach grade
$LNWIDN$ = lane width
HZRT5M = hazard rating
PC150 = 150 km before point of curvature
PC = point of curvature
MID = midpoint of curve
PT = point of tangency

Table 6 – Mean Speed Models (Poe and Mason 2000)

Boyle and Mannering (2004) explored the effect of in- and out-of-vehicle travel advisory messages (related to adverse weather and incident conditions) on mean speeds and speed deviations. The study was conducted using a full-size driving simulator that was designed to represent a multilane highway in Washington. A three-stage least squares (3SLS) method was used to determine the endogenous relationship between mean speeds and mean speed deviations. It was concluded that the travel-advisory had a negative effect on mean speeds and speed deviations. It was noted that this effect was only prevalent for the roadway sections in which the messages were presented, and that speed deviations often increased on downstream sections. The presence of vertical curves was also found to have a significant impact on mean speed and speed deviation, yielding a coefficient of -2.34 km/h.

Figueroa and Tarko (2004) investigated the effect of highway geometric characteristics on free-flow speeds on four-lane suburban and rural highways. Speed data were collected at 50 sites in Indiana for all vehicles. A random effects (RE) model was developed to predict percentile speeds and speed deviations. The model results for a stratum of percentile speeds (5th percentile through 95th percentile) are shown in Table 7. A Z_p value of zero represents the model for the 50th percentile (mean) speeds. An increase in intersection density and the presence of a rural area were associated with an increase in speed. An increase in sight distance, external clear zone, internal clear zone, and the presence of a two-way left-turn lane (TWLTL) were associated with a decrease in speed. Lower posted speed limits, when compared to the baseline speed (55 mph) were associated with lower vehicle operating speeds.

$$\begin{aligned} V_p = 54.027 &- 4.764 * PSL_{50} - 4.942 * PSL_{45} - 6.509 * PSL_{40} + 1.652 * RUR \\ &+ 1.281x10^{-3} * SD - 0.320 * INTD + 0.034 * ECLR + 0.056 * ICLR \\ &+ 5.899 * Z_p - 0.423 * \left(Z_p * PSL_{45-40}\right) - 0.464 * \left(Z_p * RUR\right) \\ &- 4.800x10^{-4} * \left(Z_p * SD\right) + 0.042 * \left(Z_p * INTD\right) - 4.220x10^{-3} \\ &* \left(Z_p * CLR\right) - 0.477 * (Z_p * TWLT) \end{aligned}$$

Where:

PSL_{50}	equal to 1 if the posted speed limit is 50 mph; 0 otherwise
PSL_{45}	equal to 1 if the posted speed limit is 45 mph; 0 otherwise
PSL_{40}	equal to 1 if the posted speed limit is 40 mph; 0 otherwise
PSL_{45-40}	equal to 1 if the posted speed limit is 40 or 45 mph; 0 otherwise
RUR	equal to 1 if the segment is in a rural area; 0 otherwise
SD	sight distance, feet
INTD	intersection density; number of intersections per mile
ECLR	external clear zone, lateral clearance distance measured from the exterior edge of the traveled way to the face of the roadside obstruction, feet
ICLR	internal clear zone, lateral clearance distance measured from the interior edge of the traveled way to the inside edge of the opposing traveled way or to the median barrier face, if a barrier is present in the median, feet
TWLT	equal to 1 if a two-way left turn median lane is present; 0 otherwise
Z_p	standardized normal variable corresponding to a selected percentile

Table 7 – Mean Speed Model (Figueroa and Tarko 2004)

Ali et al. (2006) studied the relationship between free flow speeds and geometric features on multilane urban streets. Spot speed data were collected on tangent sections of 35 four-lane urban streets in Virginia. The data only included passenger cars. Linear regression models were developed for mean and 85th-percenitle speeds. Table 8 displays the free-flow speed prediction models. An increase in segment length, the presence of a median, and an increase in posted speed limit were associated with an increase in mean and 85th percentile free-flow speeds.

Posted Speed Only

$FFS_{Mean} = 39.3 + 8.6PS_{45} + 3.7PS_{40}$ $R^2 = 0.76$

$FFS_{85th} = 39.3 + 8.6PS_{45} + 3.7PS_{40}$ $R^2 = 0.77$

Multiple Factors

$FFS_{Mean} = 37.4 + 6.8PS_{45} + 2.6PS_{40} + 13.5SL$ $R^2 = 0.87$

$FFS_{85th} = 37.4 + 8.0PS_{45} + 2.1PS_{40}+3.6MT+13.0SL$ $R^2 = 0.86$

Where:

PS_{45} = posted speed limit of 45 mph
PS_{40} = posted speed limit of 40 mph
SL = segment length (ft)
MT = median type (1 if median is divided, TWLTL; 0 otherwise)

Table 8 – Free Flow Speed Models (Ali et al. 2007)

Gong and Stamatiadis (2008) developed models to predict operating speeds on horizontal curves for rural four-lane highways. Speed data were collected for passenger cars at 76 horizontal curves in Kentucky, for both the inside and outside lanes. OLS linear regression was used to predict the 85th percentile speeds. The speed models for both the inside and outside lanes are shown in Table 9. An increase in length of curve and the presence of a surfaced shoulder was associated with an increase in 85th percentile speed for the inside lane. An increase in the approach tangent grade, the presence of a positive median barrier, and the presence of bituminous pavement were associated with a decrease in 85th percentile speed for the inside lane. An increase in curve radius and the presence of a surfaced shoulder were associated with an increase in 85th percentile speed for the outside lane. An increase in approach grade, the presence of a positive median barrier, and the presence of a curve on the approaching section were associated with a decrease in 85th percentile speed for the outside lane.

Inside Lane:

$$V_{85} = 51.520 + 1.567 * ST - 2.795 * MT - 4.001 * PT - 2.150 * AG + 2.221 * \ln(LC)$$

$R^2 = 0.6836$

$R^2_{adj} = 0.6477$

Outside Lane

$$V_{85} = 60.779 + 1.804 * ST - 2.251 * MT - 1.071 * AG - 1.519 * FC + 0.000472 * R + 2.408 * \frac{LC}{R}$$

$R^2 = 0.5015$

$R^2_{adj} = 0.4320$

Where:

V_{85}	the 85th -percentile speed (mph)
ST	shoulder type index (if the type is surfaced, $ST = 0$, else, $ST = 1$)
MT	median type index (if the type is positive barrier, $MT = 0$, else, $MT = 1$)
PT	pavement type index (if the type is bituminous, $PT = 0$, else, $PT = 1$)
AG	approaching section grade index (if the absolute grade < 0.5%, $AG = 1$, else, $AG = 0$)
LC	length of curve (ft)
FC	front curve index (if the approaching section is a curve, $FC = 1$, else, $FC = 0$)
R	curve radius (ft)

Table 9 – 85th Percentile Speed Models (Gong and Stamatiadis 2008)

Himes and Donnell (2010) studied the effect of geometric design features and traffic flow on vehicle operating speeds along multilane highways. Data were collected for passenger cars at six locations on 5 different multilane highways in North Carolina and Pennsylvania. A simultaneous equations approach was used to model mean operating speeds and speed deviations. It was concluded that this method could properly determine the endogenous relationship that exists among adjacent lane mean speeds and speed deviation, for all roadway sections. Therefore, the effect of geometric design features on mean speeds and speed deviations could be established without endogeneity bias. Models were developed for mean speed and speed deviation for both the right and left lanes. Table 10 displays the significant mean speed predictors for the simultaneous equation models, along with the direction and magnitude of their coefficients. For the right lane, an increase in the right-lane heavy vehicle percentage and the presence of a clear zone width greater than 20 feet were associated with an increase in mean speed. The presence of commercial land, the presence of a signalized intersection, a posted speed limit of 35 mph, and an increase in the number of access points within 500 feet of the site were associated with a decrease in mean speed. For the left lane, an increase in the horizontal curve length and an increase in segment access density were associated with an increase in mean speed. The presence of a TWLTL, a posted speed limit of 55 mph, and the presence of a signalized intersection were associated with a decrease in mean speed.

Right Lane	
Predictor Variable	**Mean Speed**
Constant	1.442
Logarithm of left-Lane mean speed (mph)	0.658
Logarithm of right-lane speed deviation (mph)	-0.072
Commercial indicator (1 if land use is commercial; 0 otherwise)	-0.044
Signalized intersection indicator (1 if within 1,840 ft.; else 0)	-0.025
Posted speed 35 mph (1 if posted speed 35; 0 otherwise)	-0.047
Right-lane heavy vehicle percentage (%)	0.257
Number of access points within 500 ft. of site location (number of points)	-0.007
Clear zone width indicator (1 if greater than 20 ft.; 0 otherwise)	0.026
Left Lane	
Constant	2.067
Logarithm of right-Lane mean speed (mph)	0.517
Logarithm of right-lane speed deviation (mph)	-0.078
TWLTL indicator (1 if median type if TWLTL; 0 otherwise)	-0.077
Horizontal curve length (miles)	0.089
Posted speed 55 mph (1 if posted speed 55; 0 otherwise)	-0.033
Segment access density (pts./mile)	0.0012
Signalized intersection indicator (1 if within 1,840 ft.; else 0)	-0.011

Table 10 – Mean Speed Models (Himes and Donnell 2010)

Summary

Based on the results of the previous modeling efforts that have been completed, the following can be ascertained about geometric features and roadway characteristics for trucks:

- Speed increases when the radius of horizontal curve increases;
- Speed increases when the length of the approach tangent increases;
- Speed decreases when the grade of the approach tangent increases;
- Speed decreases when the length and grade of the departure tangent increases;

The following can be ascertained for multilane highways:

- Speed increases when the radius of horizontal curve increases;
- Speed decreases when the degree of horizontal curvature increases;
- Speed increases when the length of horizontal curve increases;
- Speed increases when the length of vertical curve increases;
- Speed increases when the length of the approach tangent increases;
- Speed decreases when the grade of the approach tangent increases;
- Speed increases when the inverse of access density increases;
- Speed increases when the clear zone width increases;
- Speed increases with an increases in right lane heavy vehicle percentage;
- Speed increases (decreases) when the posted speed limit is set higher (lower) than the baseline.

These identified relationships will allow for a more concentrated selection of parameters when specifying a model for this thesis.

The most common statistical modeling method presented in previous research was OLS regression. Many authors have suggested that OLS regression fails to account for repeated speed measurements recorded at data sites, or the modeling approach does not consider the full speed distribution of speed observations at study sites. A panel data technique applied to speed data has been used to account for space and time dimensions (Tarris et al. 1998), thereby addressing issues related to repeated measurements at data collection sites. A simultaneous equations approach has been used to account for the endogenous relationships contained within a system of equations (Shankar and Mannering 1998; Himes and Donnell 2010).

Chapter 3. SITE SELECTION AND FIELD DATA COLLECTION PROCEDURES

This section describes the criteria that were used to determine the sites that were selected for inclusion in the field data collection effort. It also outlines the equipment and procedures that were used to collect the necessary data for the study.

Locations

Data were collected as part of NCHRP Project 15-39, which is intended to determine superelevation criteria for sharp horizontal curves on steep grades (Torbic et al. 2011). Speed data were collected along 19 multilane highways in Washington, California, West Virginia, Maryland, and Pennsylvania. All sites contained a tangent section with a steep grade (greater than 4 percent) that progresses into a sharp horizontal curve. A sharp curve was defined as one that is likely to influence vehicle operating speeds. For example, a curve with a horizontal alignment warning sign (with or without an advisory speed plaque) was often present at study site locations to indicate a speed differential between the posted speed limit and curve advisory speed. It is worth noting that speed data were collected on the upgrade (positive grade) at three sites. Figure 2 shows a typical data collection site. Table 11 contains additional information for each individual site.

Figure 2 – Example of Data Collection Site in West Virginia

Site #	State	Roadway name	County	Milepost range (curve)	Nearest city	Area type
WA1	WA	I-90 (WB)	Grant	137.5 - 138	Vantage	Rural
WA2	WA	I-82 (WB)	Kittitas	15.14 - 15.94	Ellensburg/Yakima	Rural
WA3	WA	I-82 (WB)	Kittitas	4.00 - 4.63	Ellensburg/Yakima	Rural
WA4	WA	I-82 (EB)	Kittitas	21.75 - 22.5	Ellensburg/Yakima	Rural
WA5	WA	US 97 (NB)	Kittitas	162.7 - 163	Ellensburg	Rural
WA6	WA	I-90 (EB)	Kittitas	131.48 - 131.69	Ellensburg	Rural
WA7	WA	US 2 (EB)	King	60.0 - 60.7	Skykomish	Rural
CA1	CA	I-5 (NB)	Kern	1.6 - 2.1	Lebec	Transition Urban to Rural
CA2	CA	SR-17 (NB)	Santa Clara	2.0 - 3.0	Los Gatos	Rural
CA3	CA	SR-17 (SB)	Santa Cruz	10.3 - 9.7	Scotts Valley	Rural
WV1	WV	I-77 (SB)	Mercer	20.6 - 21.4	Camp Creek	Rural
WV2	WV	I-68 (WB)	Monongalia	9.9 - 10.6	Cheat Lake	Rural
WV3	WV	I-79 (SB)	Kanawha	2.05 - 2.5	Mink Shoals	Rural
WV4	WV	I-77 (NB)	Kanawha	76.5 - 78.0	Cabin Creek	Rural
WV5	WV	I-64 (EB)	Kanawha	49.7 - 50.5	Institute	Urban
MD1	MD	I-68 (WB)	Garrett	5.5 - 7.0	Friendsville	Rural
MD2	MD	I-68 (WB)	Washington	74.5 - 75.0	Hancock East	Rural
MD3	MD	I-68 (WB)	Washington	72.5 - 73.5	Hancock West	Rural
PA2	PA	I-80 (EB)	Jefferson	79.5 - 80.5	Brookville	Rural

Table 11 – Data Collection Sites

Equipment and Procedures

Speed data were collected continuously from a point at least 500 feet before the PC through a point at least to the quarter-point of the horizontal curve. At some locations, speeds were collected through the midpoint of the horizontal curve. Vehicle speeds were collected using Kustom Signals laser guns. The vehicles were tracked from the rear as they drove away from the laser gun. The laser gun allowed the speed and position of a vehicle to be tracked throughout its travel between the aforementioned points. The data were downloaded directly to computers for further reduction and analysis.

Vehicle speeds were collected using either one or two laser guns, depending on the geometry of the site and the available sight distance to the traveling vehicles. If two laser guns were used, the two operators collaborated via radio communication by providing a description of the vehicle that was to be tracked through the data collection site. In this case, two files were merged during post-processing of the data in order to create a single speed profile for each vehicle.

The laser guns were operated by a researcher inside of a vehicle parked on the side of the road. The vehicle was parked in a safe location and in an inconspicuous manner, so as to not impact the naturalistic behavior of the drivers. Data were collected under normal conditions (dry roadway, no adverse weather, adequate sunlight) during the daytime – data collection at each site occurred over the course of a single weekday. Both passenger car and truck speeds were collected at each site. The vehicle type was noted in the laser gun data collection file for post-processing reference. Speed data were collected for approximately 100 (±25) passenger cars and 75 (±25) trucks at each site. Figure 3 displays a plan view of the field set-up for the speed data collection process. The position of the laser guns coincide with locations in which a vehicle can be fully tracked from 500 feet before the PC through the quarter- or midpoint of the horizontal curve.

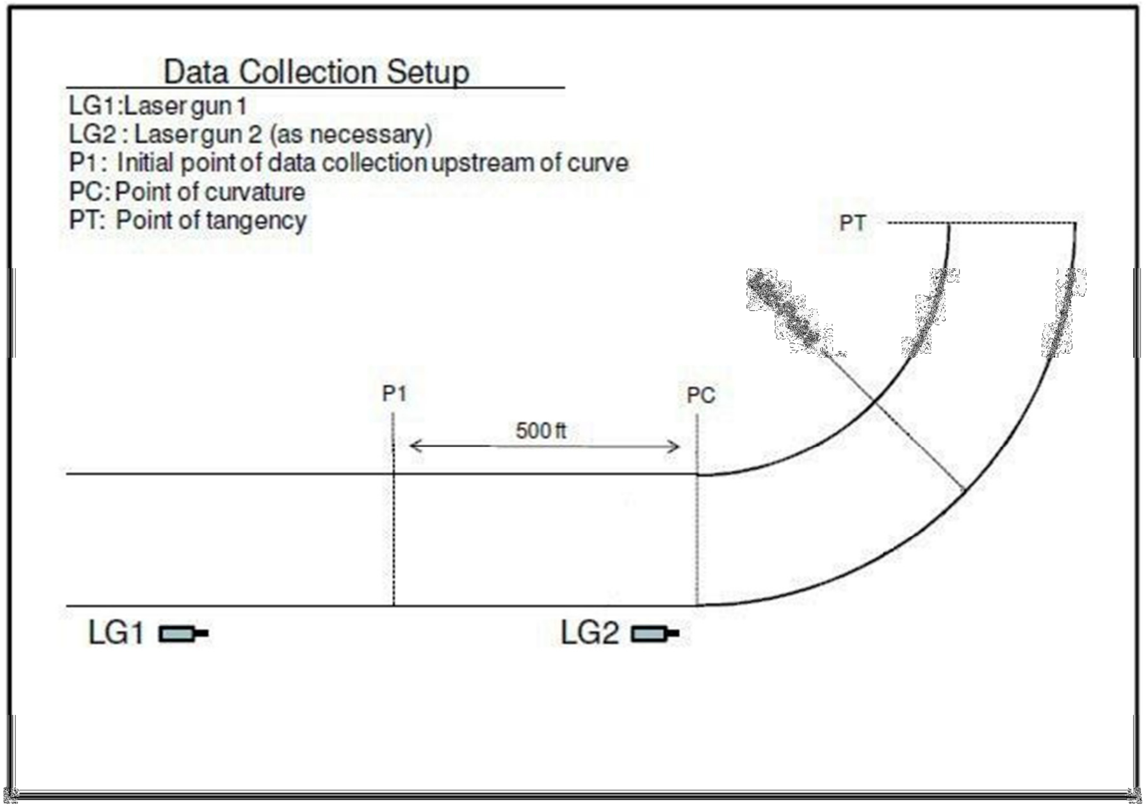


Figure 3 – Field Data Collection Setup

Geometric feature data, signage, and pavement marking information were also collected at each site. This was completed by field observation and measurement, as well as the analysis of as-built plans. The data that were collected included the following:

- Design speed
- Percent grade
- Radius of curvature
- Length of curve

- Superelevation
- Curve direction (left vs. right)
- Presence of spiral transition
- Median width
- Shoulder width
- Posted speed limit
- Presence of advisory speed plaques

These data were also uploaded to computers for further reduction and analysis. Many of the geometric design features present at the study sites will serve as predictor variables in the statistical models being estimated for this thesis. Descriptive statistics for all variables measured in the study are shown in Chapter 5 of this thesis.

Chapter 4. METHODOLOGY

This section explains the statistical analysis methods that were utilized in this thesis. OLS regression was the primary methodology used to develop speed prediction models for mean passenger car and truck speed. Simultaneous equations models were also developed to account for endogenous relationships between the dependent variables.

OLS Regression

This thesis develops models to predict mean speeds for both passenger cars and trucks at a point 300 feet before the PC and at the PC. These locations were selected to maximize the number of observations present in the analysis database (see Chapter 5 for further discussion). As previously stated, OLS regression is the predominant statistical approach used in vehicle speed prediction modeling. OLS regression is the standard linear method of representing the effects independent variables have on dependent variables. Therefore, OLS regression was used to estimate the effects that various geometric features and roadway characteristics have on mean passenger car and truck speeds for the data in this thesis. OLS regression has the following functional form:

$$Y = \alpha + \beta X + \varepsilon$$

where Y is the dependent variable, X is a vector of exogenous independent variables, α and β are vectors of estimable coefficients, and ε is the disturbance term. The parameter coefficients are estimated by minimizing the sum of the squared residuals.

OLS regression consists of five assumptions concerning the way in which data are generated. These five assumptions, as described by Kennedy (2003), are as follows:

1. The dependent variable can be calculated as a linear function of a specific set of independent variables, plus a disturbance term;
2. All disturbances have the same variance;
3. The disturbances and are not correlated with one another;
4. The observations on the independent variable(s) can be considered fixed in repeated samples;
5. There are no exact linear relationships between the independent variables.

These assumptions must hold true for the model to produce efficient and unbiased relationships between the dependent variable and the predictor variables.

Many operating speed modeling problems can be characterized as situations in which one or more of these five assumptions are violated in some way. When assumption violations occur, the OLS estimator is no longer the most efficient and unbiased statistical method available. Bias will result in an incorrect interpretation of the parameters (i.e. over- or understating the association between the dependent variable and the predictors). Inefficiency will lead to improper statistical inferences (i.e. incorrectly including or omitting independent variables in the model). If the assumptions of OLS regression are not met, alternative modeling approaches should be considered. Table 12 shows a classification of violations for each assumption, how to determine if an assumption is violated, and common alternative modeling approaches. Although this table lists several viable determination methods and alternative approaches to OLS assumption violations, only specific methods will be utilized for violation testing in this thesis. Each is described in Chapter 6 when presenting the results of the passenger car and truck operating speed models.

Ass.	Violations	Determination Method	Alternative
1	• Wrong regressors • Nonlinearity • Parameter inconstancy	• T- or F-statistic test • Regression specification error test (RESET)	• Variable Transformation • Computer-assisted iterative technique
2	• Serial Correlation	• Durbin-Watson statistic • Breusch-Godfrey Test	• Cochrane-Rocutt Iterative Least Squares • Durbin's Two-Stage Method • Hildreth-Lu Search Procedure • Maximum Likelihood (ML)
3	• Heteroskedasticity	• Visual inspection of residuals • Goldfeld-Quandt Test • Breusch-Pagan Test • White Test	• Weighted Least Squares approach • Heterskedasticity-consistent standard errors (HCSE)
4	• Simultaneous equations	• Hausman Test • Compare OLS with 2SLS	• Seemingly Unrelated Regression Estimation (SURE) • Indirect Least Squares (ILS) • Two-stage Least Squares (2SLS) • Three-stage Least Squares (3SLS) • Maximum Likelihood (ML)
5	• Perfect multicollinearity	• Inspection of correlation matrix • Condition Index	• Add or reduce parameters • Factor analysis

Table 12 – OLS Regression Assumption Violations (Kennedy 2003)

A model specifying wrong regressors occurs when it omits a relevant independent variable or it includes an irrelevant variable. This causes bias in the coefficients of the remaining independent variables, leading to an incorrect interpretation of the effect on the dependent variables. Serial correlation between the error terms occurs when independent variables contain a time-series element. This causes high standard errors in the model parameters. Heteroskedasticity occurs when the residuals are not distributed identically.

This invalidates statistical tests of significance and leads to incorrectly including or omitting independent variables in the model. Simultaneous equations arises when the dependent variable is determined by the simultaneous interaction of several variables, instead of being mutually dependent on the predictor variables. This causes incorrect parameter estimates since the model will be underspecified. Multicollinearity results when two predictor variables have an exact linear relationship. This yields inefficient parameters due to the large variances that arise in their estimation.

3SLS Approach

It has been shown in previous research that in-lane mean speeds are affected by adjacent-lane mean speeds (Shankar and Mannering 1998). It is hypothesized that an endogenous relationship exists between passenger cars and trucks for this thesis, as the speed data were collected at the same points along the highway at the same time. This suggests that the mean speeds of passenger cars (trucks) should not only be a function of the geometric characteristics of the highway, but also a function of the mean speeds of trucks (passenger cars) in the same or adjacent lanes. Therefore, the endogenous relationship between passenger cars and trucks should be addressed in the regression equations used to predict the speed relationships simultaneously. This is instituted by introducing an instrumented variable that accounts for the contemporaneous correlation between the two equations.

The structural equation system for this study will, in general, be written as follows:

$$s_{pc} = \alpha + \beta x + \gamma \bar{u}_{tr} + \varepsilon \qquad (1)$$

$$s_{tr} = \alpha + \beta x + \gamma \bar{u}_{pc} + \varepsilon \qquad (2)$$

$$\bar{u}_{tr} = \delta + \pi x + \upsilon \qquad (3)$$

$$\bar{u}_{pc} = \delta + \pi x + \upsilon \qquad (4)$$

where s_{pc} is the mean speed of a passenger car, s_{tr} is the mean speed of a truck, x is a vector of exogenous variables influencing mean speeds for cars or trucks, $\bar{u}_{tr}$ is a vector of mean speeds for trucks influencing the mean speeds of passenger cars, $\bar{u}_{pc}$ is a vector of mean speeds for passenger cars influencing the mean speeds of trucks, ε and v are disturbance terms, and α, β, γ, δ, and π are vectors of estimable coefficients. Equation (1) specifies a model in which the mean speeds of passenger cars are endogenous with the mean speeds of trucks. Equation (2) specifies a model in which the mean speeds of trucks are endogenous with the mean speeds of passenger cars. Equations (3) and (4) represent the reduced form parameters for the instrumented variables of mean truck speed and mean passenger car speed, respectively.

To estimate equations (1) and (2), a full information three-stage least squares (3SLS) approach will be utilized. The steps for model estimation using a 3SLS approach, detailed by Kennedy (2003), are as follows:

1. Complete a 2SLS estimate of the equation system to obtain the instrumented variables.

2. Use the 2SLS estimates to obtain the equation system's disturbance terms, and use these error terms to estimate the contemporaneous variances-covariance matrix of the structural equations' disturbance terms.
3. Complete a generalized least-squares (GLS) approach in order to estimate the model coefficients, using the estimated contemporaneous variance-covariance matrix for the disturbances.

This method estimates the identified structural equations as a set, instead of individually as associated with the two-stage least squares (2SLS) approach. It is expected that there will be contemporaneous correlation between the disturbance terms, since the mean speeds of passenger cars and trucks are generated simultaneously. This correlation causes a 2SLS approach to produce inefficient parameter estimates, whereas a 3SLS approach accounts for it. This makes the 3SLS modeling approach superior to the 2SLS, as there is no efficiency loss regardless of the presence of contemporaneous correlation among the disturbance terms. Therefore, a 3SLS approach will be used over a 2SLS approach for data modeling in this thesis.

Chapter 5. DATA

The data that were collected for this thesis were maintained in a large, electronic database. The speed data that were collected were for continuous speed measurements for passenger cars and trucks as they traversed from the approach tangent through the horizontal curve. The actual location of the vehicles that were collected varied with respect to the PC for each site. Table 36 in Appendix A displays a count of observations at each site in 100 foot intervals with respect to the PC. A spot speed measurement was extracted from the data at 300 feet before the PC and at the PC. It was determined that these two points would provide a clear interpretation of mean passenger car and truck speed on the approach tangent and on the horizontal curve. These two points were chosen because they provided the maximum number of actual speed observations. Speed observations at sites that did not include these two points were then linearly-interpolated during the data reduction process.

The dependent variable for the passenger car and truck models is vehicle speed collected at a point 300 feet before the PC and at the PC. These points will be referred to as Point 1 and Point 2, respectively, for the remainder of this thesis. The descriptive statistics for the dependent variable (speed in mph) for both cars and trucks are shown in Table 37 in Appendix A. It includes the number of observations, the mean speed, the standard deviation of the speed, and the minimum and maximum speeds at each of the 19 sites for the entire data set. As shown, there are a total of 1509 passenger car speeds and 1042 truck speeds in the database. The mean speeds for the passenger cars are higher than the mean speeds for the trucks by 7.58 mph at Point 1 and 7.46 mph at Point 2. The standard deviation for trucks is higher than the standard deviation for passenger cars at both points, signifying that there is a wider distribution of trucks speeds than passenger cars speeds.

Figures 18 through 21 in Appendix A show a histogram of the distribution of passenger car and truck speeds collected at Point 1 and Point 2. As shown, the passenger car speeds appear to be normally-distributed at both points. The truck speed distributions appear to be skewed right at both point locations. Therefore, it is clear that the data for the dependent variable for truck speed is not normally-distributed. This issue is further explored when presenting the results of the statistical analysis in Chapter 6 of this thesis.

Chapter 3 included a list of possible independent variables that were collected from the study sites. However, some of these variables were excluded from consideration in statistical models due to incomplete data. Table 38 in Appendix A displays the descriptive statistics of the independent variables that were included in the final, reduced database used for statistical modeling. The table includes the mean, standard deviation, minimum, and maximum values for each variable. These variables were constant at each site in which data were collected; therefore, there are a total of 19 unique observations for each independent variable.

Table 39 in Appendix A displays the correlation matrix for all independent variables considered in the model building process. This matrix is used to test the OLS assumption of no perfect correlation between independent variables. A value of 0.8 was used as the threshold to detect a high-level of correlation between specific independent variables (Kennedy 2003). As shown, the only correlation coefficients above this threshold occurred between the posted speed limits of trucks and passenger cars. This was anticipated since only a small percentage of the sites contained posted speed limits that were different between trucks and passenger cars (excluding the advisory speeds listed on horizontal curve signs). However, there were some posted speed limit indicators that were combined to create a new posted speed limit indicator, which will be discussed in the analysis results presented in Chapter 6 of this thesis.

Chapter 6. ANALYSIS RESULTS

This section contains the results of the statistical modeling that was performed for this thesis. The OLS regression results and discussion are presented first, followed by the 3SLS analysis. An iterative, stepwise regression was first performed on the data in order to attain the best independent variables with which to begin the model building process. Each variable was judged by its statistical significance in relation to truck and/or passenger car speed using the t-statistic. A relatively relaxed t-statistic was used for this thesis, with p-value of 0.3 used as the significance threshold. It was determined that this would allow for more relationships to be conveyed through this analysis, even if the 95 percent confidence interval suggests a relationship may be absent in the data. Each model was then judged based on its goodness-of-fit (R^2_{adj}) value, with a model having an R^2_{adj} value closer to 1 being more favorable than a model having an R^2_{adj} value closer to 0. Models were also selected based on parsimony, with models having less variables held higher than models with more variables given no change in the goodness-of-fit.

Ordinary Least Squares Regression

Ordinary least squares regression was first performed in order to estimate the effects of all exogenous variables on speeds. Four OLS regression models were developed for this thesis. The models included the mean passenger car speed at Point 1, the mean passenger car speed at Point 2, the mean truck speed at Point 1, and the mean truck speed at Point 2.

Passenger Car Speed Models

The results of the model for mean operating speed at Point 1 for passenger cars are shown in Table 13. The model had an R^2_{adj} of 0.501. Independent variables were chosen based on the results of the t-test and the respective p-value. The variables selected for this model had a p-value of less than 0.3 and a coefficient that was logical with respect to sign convention (i.e., direction of statistical association).

Variable	**Coefficient (β)**	**Standard Error**	**t-statistic**	**p-value**
Constant	64.132	41.890	41.890	< 0.001
InverseRadius (feet)	-7210.676	651.447	-11.07	< 0.001
PercentGrade (%)	-0.399	0.047	-8.43	< 0.001
CarPosted60 Indicator (1 if car posted speed limit is 60 mph; 0 otherwise)*	5.183	0.798	6.50	< 0.001
CarPosted65 Indicator (1 if car posted speed limit is 65 mph; 0 otherwise)*	6.744	0.969	6.96	< 0.001
CarPosted70 Indicator (1 if car posted speed limit is 70 mph; 0 otherwise)*	7.383	0.890	8.30	< 0.001
InverseSuper (%)	-7.235	1.973	-3.67	< 0.001
*The baseline is a car posted speed limit of 55 mph. A positive value for the CarPosted60, CarPosted65, and CarPosted70 indicator variables shows that mean passenger car operating speeds at Point 1 are higher on roadways with posted speed limits of 60, 65, and 70 mph, when compared to the baseline.				
N	1509			
R^2_{Adj}	0.501			
Root MSE	5.490			

Table 13 – OLS Mean Speed Prediction Model for Passenger Cars at Point 1

The Ramsey RESET test is insignificant (p-value of 0.0632 is greater than α=0.05); therefore, the null hypothesis that the model has no omitted variables cannot be rejected. The Durbin-Watson statistic is 1.876 > d_u = 1.831 (upper limit for K = 6 independent variables); therefore, there is no positive serial correlation present in the passenger car data used at Point 1 to estimate mean operating speeds. Figure 4 displays a histogram of the residuals for this model and Figure 5 displays a normal probability plot of the residuals for this model. These figures show that the residuals follow a normal distribution. Figure 6 displays a graph of the residuals versus the fitted values, which shows no fan-shape or obvious pattern; therefore, it can be concluded that there is no heteroskedasticity without further testing. The assumption of endogeneity will be addressed in the systems of equations modeling.

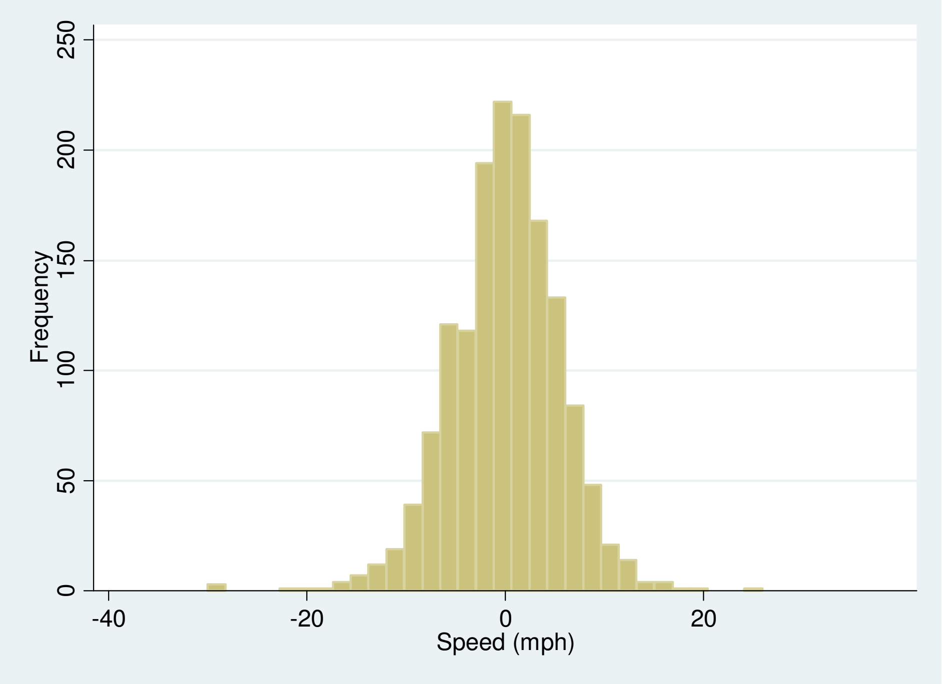


Figure 4 – Histogram of Residuals for Mean Passenger Car Speed at Point 1

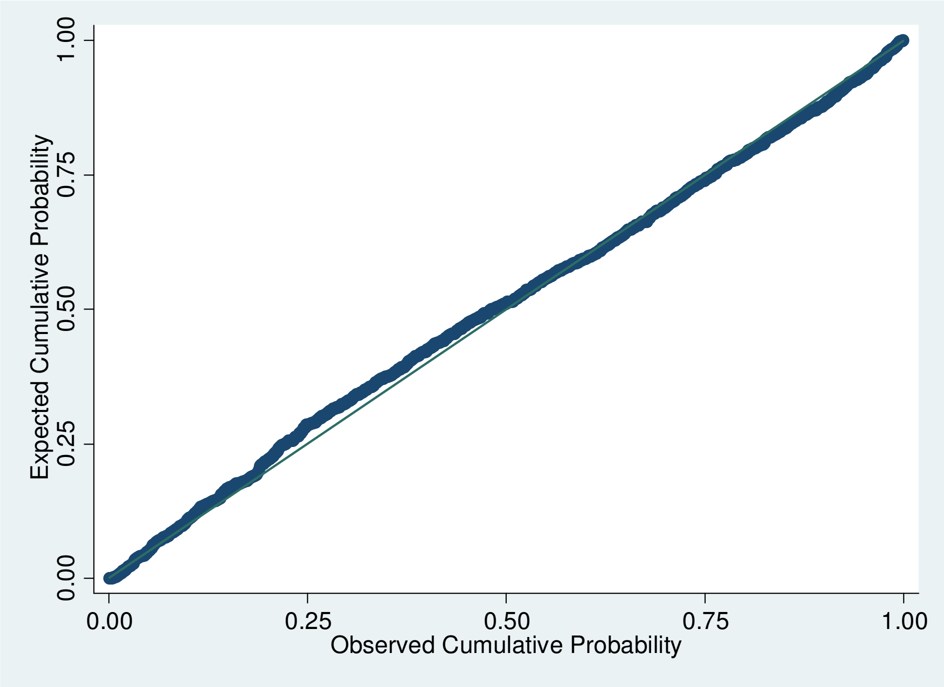


Figure 5 – Normal Probability Plot of Residuals for Mean Passenger Car Speed at Point 1

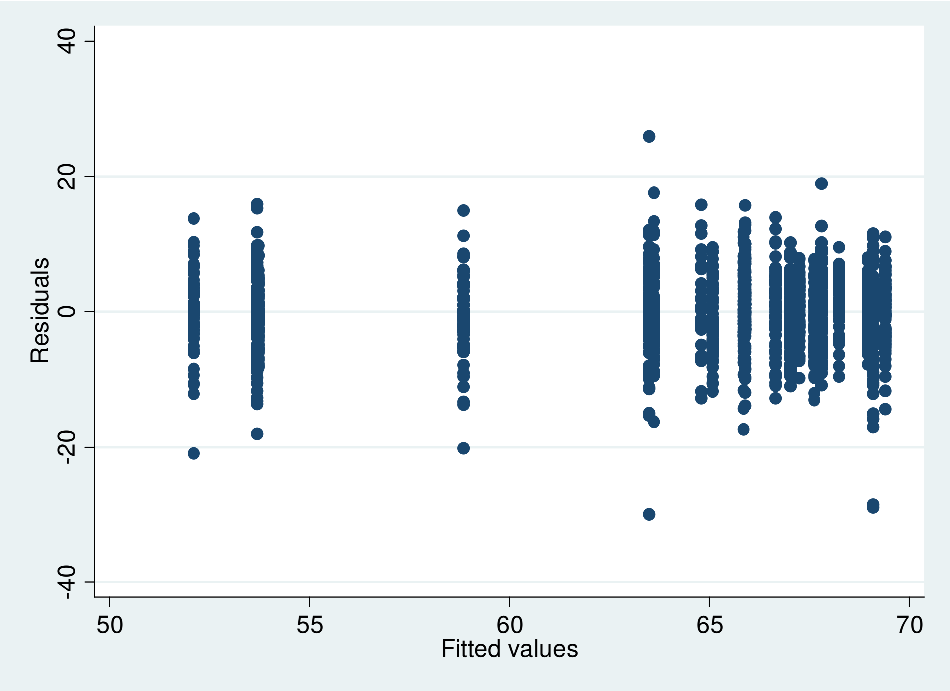


Figure 6 – Residuals vs. Fitted Values Plot for Passenger Cars at Point 1

The InverseRadius coefficient indicates that for every one foot increase in the radius of horizontal curve, the mean passenger car operating speed at Point 1 will decrease by 1/7210.676 mph, holding all other variables constant. In other words, as the radius of the horizontal curve decreases, mean passenger car speeds will also decrease. This supports previous research that horizontal curve radius and passenger car speed have a direct relationship (Gong and Stamatiadis 2008). This relationship signifies that passenger car speeds are lower on approach tangents that approach sharp horizontal curves, as higher speeds would lead to higher side friction demand and lateral acceleration, which may approach driver comfort levels for design side friction (AASHTO 2004).

The PercentGrade coefficient indicates that for every one percent increase in percent grade on the approach tangent, the mean passenger car operating speed at Point 1 will decrease by 0.399 mph, holding all other variables constant. This supports previous research that grade and passenger car speed have an inverse relationship (Poe and Mason 2000). Positive grades (upgrades) decrease passenger car speeds and negative grades (downgrades) increase passenger car speeds. This is due to gravitational effects that are present on vertical gradients and cause acceleration (or deceleration) on the vehicle (Donnell et al. 2001).

The CarPosted60 indicator coefficient indicates that a posted speed limit of 60 mph is associated with a mean passenger car operating speed that is 5.183 mph higher than the baseline posted speed limit of 55 mph, holding all other variables constant. The CarPosted65 indicator coefficient indicates that a posted speed limit of 65 mph is associated with a mean passenger car operating speed that is 6.744 mph higher than the baseline posted speed limit of 55 mph, holding all other variables constant. The

CarPosted70 indicator coefficient indicates that a posted speed limit of 70 mph is associated with a mean passenger car operating speed that is 7.383 mph higher than the baseline of posted speed limit of 55 mph, holding all other variables constant. Overall, the posted speed limit indicator variables show that higher posted speed limits are associated with higher mean operating speeds for passenger cars at Point 1.

The InverseSuper coefficient indicates that for every one percent increase in the inverse of the superelevation rate on the horizontal curve, the mean passenger car speed at Point 1 will decrease by 1/7.235. By way of explanation, as the superelevation decreases mean passenger car speed will also decrease. This coefficient shows that passenger car speeds are being influenced directly by the amount of superelevation present on the horizontal curve at Point 1. There has been no previously specified relationship between the superelevation and passenger car speed on tangent sections. One possible explanation for this relationship is that, on high-speed roadways, spiral curve and tangent-to-curve transitions often begin several hundred feet before the PC or SC (simple curve radius). As such, the pavement cross-slope is beginning to change at this location; therefore, it was expected that the cross-slope will be associated with driver speed selection before the PC or SC.

Table 14 displays the results of the model for mean operating speed at Point 2 for passenger cars. The model had an R^2_{adj} of 0.556. Independent variables were chosen based on the results of the t-test and the respective p-value. The variables selected for this model had a p-value of less than 0.3 and a coefficient that was logical with respect to sign convention (i.e., direction of statistical association). The Ramsey RESET test was not statistically significant (p-value of 0.0630 is greater than $\alpha=0.05$); therefore, the null hypothesis that the model has no omitted variables cannot be rejected. The Durbin-Watson statistic is 1.861 > d_u = 1.841 (upper limit for K = 7 independent variables); therefore, there is no positive serial correlation present in the passenger car operating speed data collected at Point 2. Figure 7 displays a histogram of the residuals for this model and Figure 8 displays a normal probability plot of the residuals for this model. These figures show that the residuals follow a normal distribution. Figure 9 displays a graph of the residuals versus the fitted values, which shows no fan-shape or obvious pattern; therefore, it can be concluded that there is no heteroskedasticity without further testing. The assumption of endogeneity will be addressed in the systems of equations modeling.

Variable	**Coefficient (β)**	**Standard Error**	**t-statistic**	**p-value**
Constant	45.059	8.233	5.470	< 0.001
InverseRadius (feet)	-6319.590	1080.725	-5.85	< 0.001
PercentGrade (%)	-0.431	0.050	-8.55	< 0.001
CarPosted6065 Indicator (1 if car posted speed limit is 60 or 65 mph; 0 otherwise)*	6.040	0.995	6.08	< 0.001
CarPosted70 Indicator (1 if car posted speed limit is 70 mph; 0 otherwise)*	8.830	1.202	7.10	< 0.001
AdvisoryPresent (1 if advisory speed sign is present; 0 otherwise)	-2.698	0.648	-4.16	< 0.001
LW (ft)	1.573	0.600	2.62	0.009
InverseSuper (%)	-8.228	1.927	-4.27	< 0.001

*The baseline is a car posted speed limit of 55 mph. A positive value for the CarPosted6065 and CarPosted70 indicator variables shows that mean passenger car operating speeds at Point 2 are higher on roadways with posted speed limits of 60, 65, and 70 mph, when compared to the baseline.

N	1509
R^2_{Adj}	0.556
Root MSE	5.424

Table 14 – OLS Mean Speed Prediction Model for Passenger Cars at Point 2

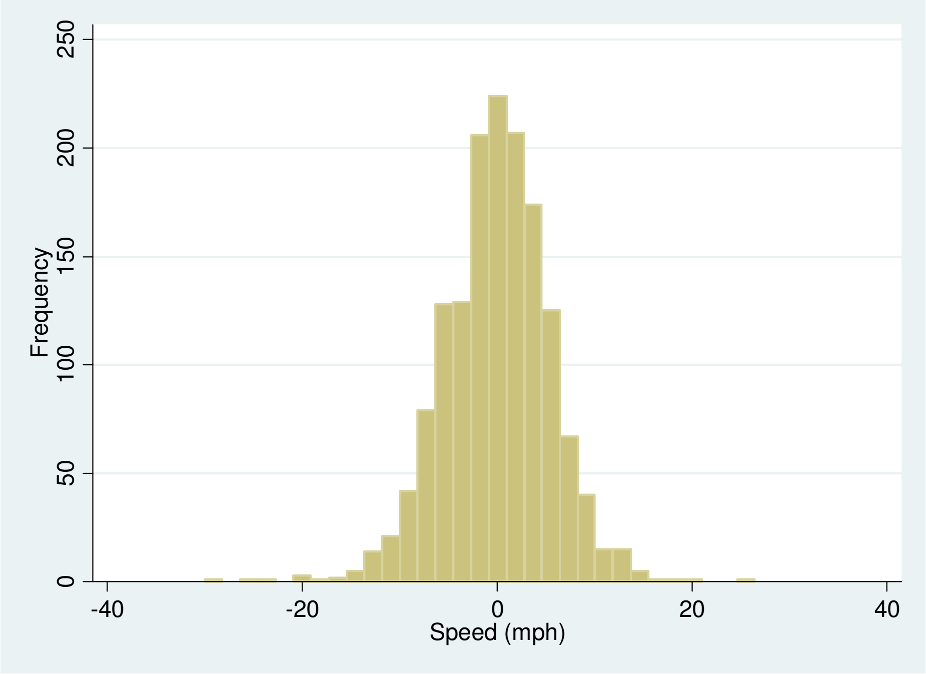


Figure 7 – Histogram of Residuals for Mean Passenger Car Speed at Point 2

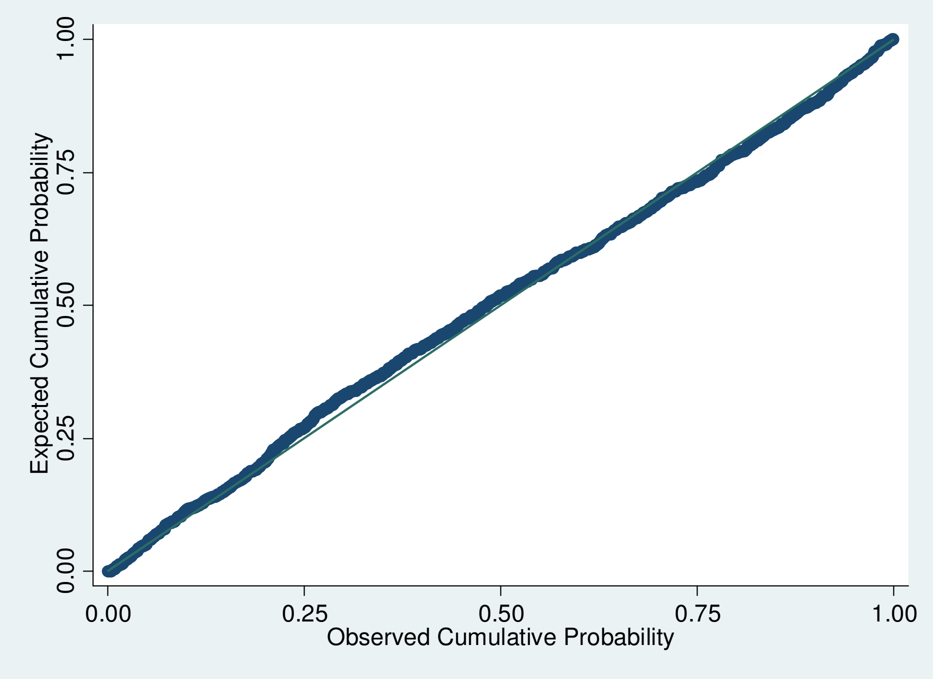


Figure 8 – Normal Probability Plot of Residuals for Mean Passenger Car Speed at Point 2

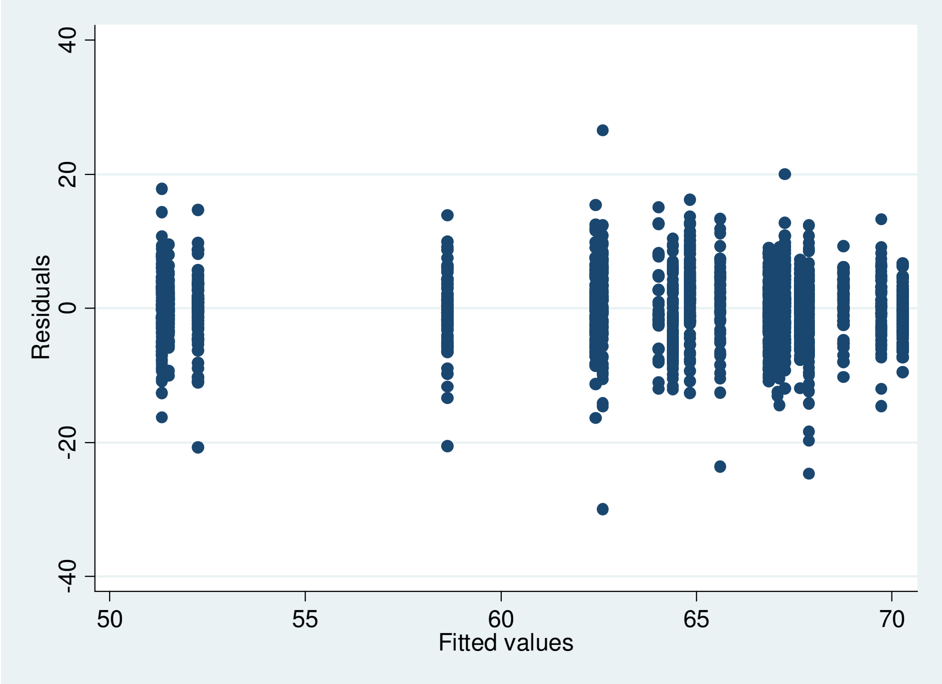


Figure 9 – Residuals vs. Fitted Values Plot for Passenger Cars at Point 2

The InverseRadius coefficient indicates that for every one foot increase in the radius of horizontal curve, the mean passenger car operating speed at Point 2 will decrease by 1/6319.590 mph, holding all other variables constant. In other words, as the radius of the horizontal curve decreases, mean passenger car speeds will also decrease. This relationship signifies that passenger car speeds are lower on sharp horizontal curves, as higher speeds would lead to higher side friction demand and lateral acceleration, which may approach driver comfort levels for design side friction (AASHTO 2004).

The PercentGrade coefficient indicates that for every one percent increase in the percent grade on the approach tangent, mean passenger car operating speeds at Point 2 will decrease by 0.431 mph, holding all other variables constant. This supports previous research that grade and passenger car speeds have a negative association (Poe and Mason 2000). Positive grades (upgrades) decrease passenger car speeds and negative grades (downgrades) increase passenger car speeds. This is due to gravitational effects that are present on vertical gradients and cause acceleration (or deceleration) on the vehicle (Donnell et al. 2001). This indicates that the percent grade of the approach tangent is still negatively influencing speeds as the cars reach the PC.

The CarPosted6065 indicator coefficient indicates that a posted speed limit of 60 mph or 65 mph is associated with a mean passenger car operating speed that is 6.040 mph higher than the baseline posted speed limit of 55 mph, holding all other variables constant. This indicator variable was obtained by combining Carposted60 and Carposted65 into a single predictor. This was performed for parsimonious reasons, since both Carposted60 and Carposted65 had an almost identical effect on the mean operating speed of passenger cars at Point 2. The CarPosted70 indicator coefficient indicates that a posted speed limit of 70 mph is associated with a mean passenger car operating speed that is 8.830 mph higher than the baseline of posted speed limit of 55 mph, holding all other variables constant. Overall, the posted speed limit indicator variables show that higher posted speed limits are associated with higher mean operating speeds for passenger cars at Point 2.

The AdvisoryPresent indicator coefficient shows that the presence of a reduced speed advisory warning sign is associated with a mean passenger car operating speed that is 2.698 mph lower than the baseline condition of no reduced speed advisory sign present. This indicates that the presence of an advisory speed warning sign located before the horizontal curve is decreasing mean passenger car operating speeds at Point 2. This variable represents the effect on mean passenger car speed due to a speed advisory sign, which is required when the advisory speed (necessary to reduce side friction demand on the horizontal curve) is 10 mph or more below the posted speed limit (FHWA 2012).

There has been no previously established relationship between the presence of an advisory speed warning sign and passenger car speeds on multilane highways.

The LW coefficient indicates that for every one foot increase in lane width, the mean passenger car operating speed at Point 2 increases by 1.573 mph. This finding shows that as lane width increases, so does the mean passenger car speed. This supports previous research that lane width and passenger car speeds have a direct relationship (Poe and Mason 2000). This also coincides with the Highway Capacity Manual (HCM) free-flow speed estimation method for highway facilities, which states that narrower lane widths will reduce free-flow speeds (TRB 2000).

The InverseSuper coefficient specifies that for every one percent increase in the inverse of the superelevation rate on the horizontal curve, the mean passenger car speed at Point 1 will decrease by 1/8.228. This means that as the superelevation decreases mean passenger car speed will also decrease. This direct relationship between superelevation and passenger car speed confirms previous research from studies performed on horizontal curves on two-lane rural highways (Medina and Tarko 2007; Voigt and Krammes 1996). This coefficient shows that passenger car speeds are being influenced directly by the amount of superelevation present on the horizontal curve at Point 2. This is most likely due to the fact that an increase in superelevation on a horizontal curve will decrease the amount of lateral acceleration on the vehicle. This allows drivers to travel faster before the amount of lateral acceleration hits a threshold that causes too much discomfort (AASHTO 2004).

Truck Speed Models

The results of the model for mean operating speed at Point 1 for trucks are outlined in Table 15. The model had an R^2_{adj} of 0.541. Independent variables were chosen based on the results of the t-test and the respective p-value. The variables selected for this model had a p-value of less than 0.3 and a coefficient that was logical in both sign and magnitude. The Ramsey RESET test is statistically significant (p-value of < 0.0001 is less than α=0.05); therefore, the null hypothesis that the model has no omitted variables is rejected. No variable set in the collected data was able to conclude H_o for mean truck speeds at Point 1. This will be further addressed in the recommendations section of this thesis. The Durbin-Watson statistic is 1.609 < d_L = 1.686 (lower limit for K = 8 independent variables); therefore, we can reject the null hypothesis and conclude that the data contain negative serial correlation. A graph of the residual versus the observation order, which is displayed in Figure 10, was produced to assess the serial correlation present in the data. As shown, there is a pattern in the residuals. Figure 11 displays a histogram of the residuals for this model and Figure 12 displays a normal probability plot of the residuals for this model. As shown in these graphics, the residuals appear to deviate from normality. This is confirmed in a graph of the residuals versus the fitted values, which can be seen in Figure 13. These graphics display heteroskedasticity among the residuals, with the variance decreasing as the fitted values increase. The Breusch-Pagan test for heteroskedasticity outcome was statistically significant (p-value of < 0.0001 is less than α=0.05); therefore, the null hypothesis that the residuals are homoskedastic (i.e., have constant variance among all observations) is rejected. The assumption of endogeneity will also be addressed in the systems of equations modeling.

Violating the assumptions of no omitted variables, no serial correlation, and constant variance of the residuals produces biased regression coefficients and inefficient standard errors, which may lead to incorrect model interpretation. These OLS assumption violations for this model are addressed below.

Variable	**Coefficient (β)**	**Standard Error**	**t-statistic**	**p-value**
Constant	17.861	12.666	1.41	0.159
InverseRadius (feet)	-6564.193	1201.205	-5.46	< 0.001
PercentGrade (%)	-1.527	0.061	-25.16	< 0.001
TruckPosted50 Indicator (1 if car posted speed limit is 50 mph for trucks; 0 otherwise)*	3.537	1.894	1.87	0.062
TruckPosted55 Indicator (1 if car posted speed limit is 55 mph for trucks; 0 otherwise)*	5.619	1.953	2.88	0.004
TruckPosted6065 Indicator (1 if car posted speed limit is 60 or 65 mph for trucks; 0 otherwise)*	13.343	1.795	7.43	< 0.001
TruckPosted70 Indicator (1 if car posted speed limit is 70 mph for trucks; 0 otherwise)*	18.055	1.980	9.12	< 0.001
AdvisoryPresent (1 if advisory speed sign is present; 0 otherwise)	-1.968	0.970	-2.03	0.043
LW (ft)	2.337	0.957	2.44	0.015
*The baseline is a car posted speed limit of 35 mph. A positive value for the TruckPosted50, TruckPosted55, TruckPosted6065, and TruckPosted70 indicator variables shows that mean passenger car operating speeds at Point 1 are higher on roadways with posted speed limits of 50, 55, 60, 65, and 70 mph, when compared to the baseline.				
N	1509			
R^2_{Adj}	0.541			
Root MSE	7.179			

Table 15 – OLS Mean Speed Prediction Model for Trucks at Point 1

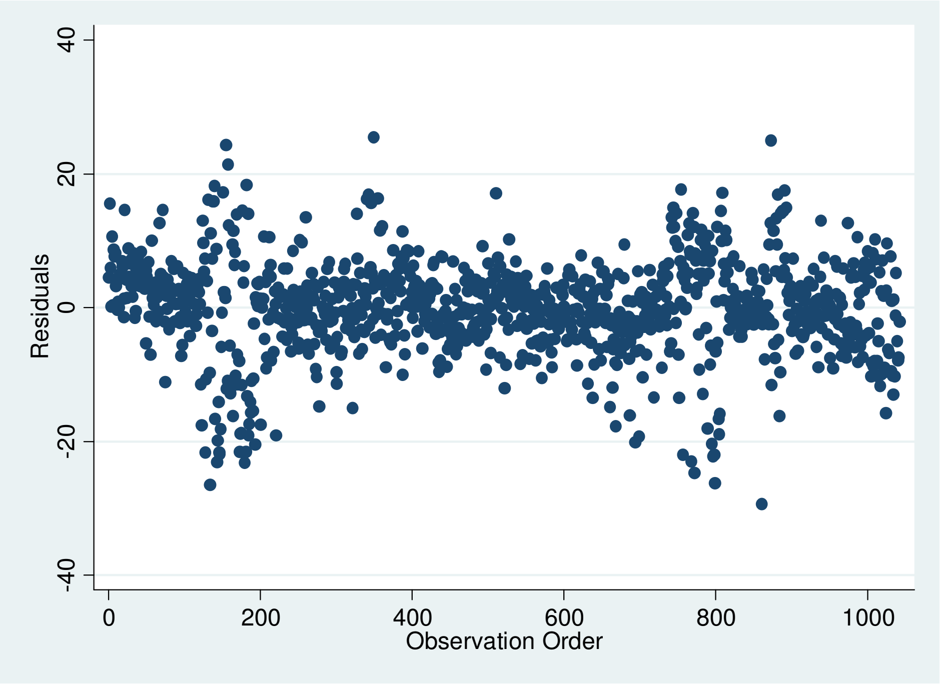


Figure 10 – Residuals vs. Observation Order Plot for Mean Truck Speed at Point 1

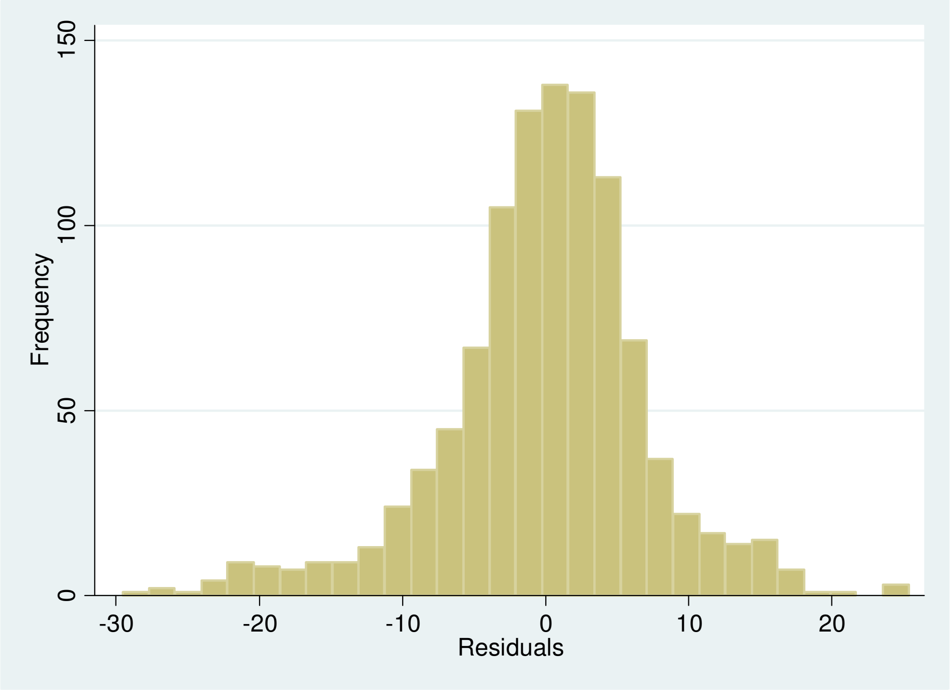


Figure 11 – Histogram of Residuals for Mean Trucks Speed at Point 1

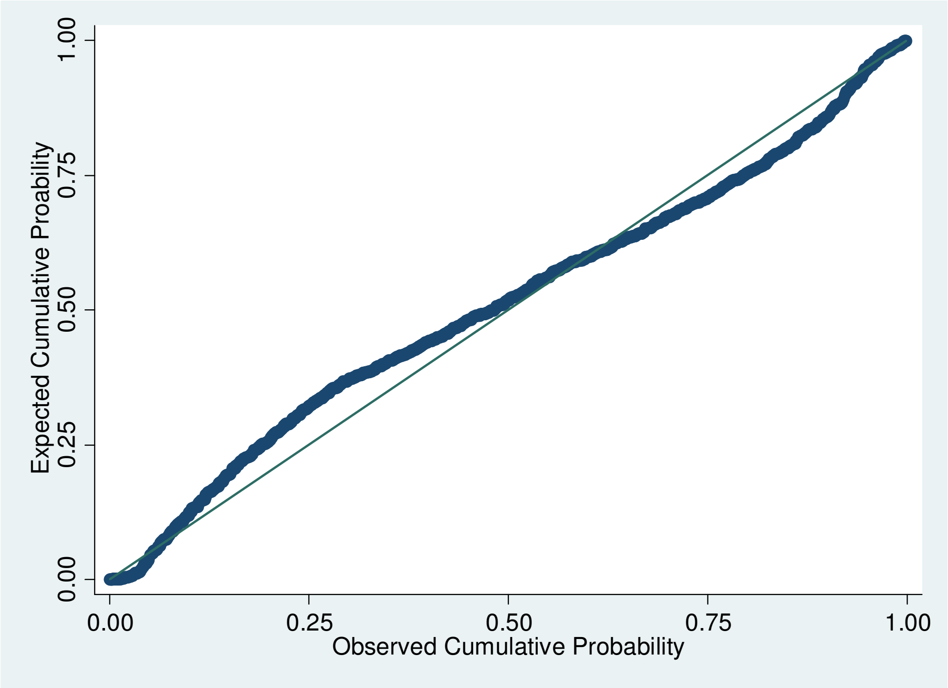


Figure 12 – Normal Probability Plot of Residuals for Mean Truck Speed at Point 1

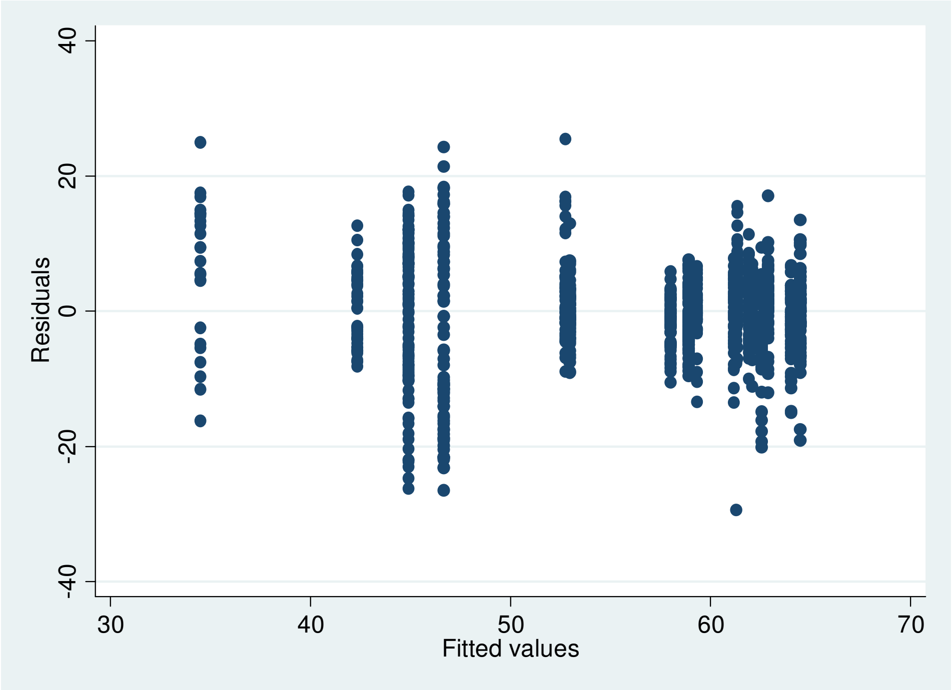


Figure 13 – Residuals vs. Fitted Values Plot for Mean Truck Speed at Point 1

The assumption tests for the OLS model for trucks at Point 1 indicate that there is a time-series factor within the residuals. This violates the OLS assumption of no serial correlation among the disturbance terms. An inspection of the residual versus observation order plot in Figure 14 shows that the residual values do contain correlation; however, this only occurs in segments. This illustrates that the serial correlation is occurring due to the fact that the data are ordered according to site. Therefore, the residuals are correlated based on the variance in the observed speeds within each site. This is exacerbated by the fact that there are only 19 unique sites in the data set. It can be concluded that the serial correlation is limited to specific sections of the data, and not contained in the overall data set for truck speeds at Point 1. Even though this will cause inefficient standard errors, it will not affect the parameter coefficients.

The assumption tests for the OLS model for trucks at Point 1 indicate that there is heteroskedasticity among the residuals. This violates the OLS assumption of equal variance among the disturbances terms. An inspection of the residual versus fitted value plot shows that the variance decreases as the fitted values increase. At sites in which the OLS model predicts a relatively low speed, the variance in the fitted value is higher than sites in which the model predicts a relatively high speed. This disparity is most likely caused by the three sites (WA5, WA7, and MD2) in the data set that contain a positive grade. Table 16 displays descriptive statistics for the speed data from Table 37 in Appendix A, but with these three sites separated from the rest. As shown, average mean truck speed at Point 1 for the three sites with a positive grade is 14.9 mph less than the sites containing a negative grade. This indicates that sites with positive grades contain smaller fitted values. More importantly, the average truck speed standard deviation at

Point 1 for the three sites with a positive grade is 6.99 mph greater than the sites containing a negative grade. This indicates that the variance of the speeds observed at the sites with positive grades is much higher than the sites with negative grades. This is most likely due to the variability in the weight-to-horsepower ratio of fully loaded trucks versus empty trucks observed at these sites. It can be concluded that the heteroskedasticity in the residuals of the OLS model for mean truck speed at Point 1 is caused by the large standard deviation at sites with positive grades. This may cause independent variables to be incorrectly omitted or included in the model. However, this will be mostly accounted for by the use of a relaxed p-value for the models in this thesis.

Negative Grade			**Positive Grade**		
Site	**Mean**	**Std Dev**	**Site**	**Mean**	**Std Dev**
WA1	56.51	3.62	WA5	46.19	11.53
WA2	60.73	4.61	WA7	40.51	10.65
WA3	58.48	6.48	MD2	42.80	13.80
WA4	59.02	4.31	**Average**	**43.17**	**12.00**
WA6	60.96	4.99			
CA1	52.98	3.98			
CA2	42.37	5.49			
CA3	41.31	7.30			
WV1	62.34	5.03			
WV2	55.88	7.33			
WV3	63.62	4.66			
WV4	58.25	4.09			
WV5	64.26	5.08			
MD1	63.06	3.54			
MD3	64.60	5.43			
PA2	65.52	4.18			
Average	**58.12**	**5.01**			

Table 16 – Descriptive Statistics for Sites with Positive and Negative Percent Grades at Point 1

The InverseRadius coefficient indicates that for every one unit increase in the radius of horizontal curve, the mean truck operating speed at Point 1 will decrease by 1/6564.193 mph, holding all other variables constant. In other words, as the radius of the horizontal curve decreases, mean truck speeds will also decrease at Point 1. This supports previous research that horizontal curve radius and mean truck speed are correlated (Donnell et al. 2001). This coefficient represents the effect of the curve radius on the truck's ability to transverse a horizontal curve while maintaining enough side friction supply to prevent skidding or rollover (Harwood et al. 2003).

The PercentGrade coefficient indicates that for every one percent increase in percent grade on the approach tangent, mean truck operating speeds at Point 1 will decrease by 1.527 mph, holding all other variables constant. This supports previous research that approach tangent grade and truck operating speed are negatively correlated (Donnell et al. 2001). Negative grades (downgrades) cause mean truck speeds to increase due to an increase in kinetic energy that cannot be fully absorbed through braking or engine drag. Positive grades (upgrades) decrease mean truck speeds due to the limitations on the truck's weight-to-horsepower ratio to counteract gravitational acceleration (Harwood et al. 2003).

The TruckPosted50 indicator coefficient indicates that a posted speed limit of 50 mph is associated with a mean truck operating speed that is 3.537 mph higher than the baseline of posted speed limit of 35 mph, holding all other variables constant. The TruckPosted55 indicator coefficient indicates that a posted speed limit of 55 mph is associated with a mean truck operating speed that is 5.619 mph higher than the baseline of posted speed limit of 35 mph, holding all other variables constant. The TruckPosted6065 indicator coefficient indicates that a posted speed limit of 60 mph or 65 mph is associated with a mean truck operating speed that is 13.343 mph higher than the baseline posted speed limit of 35 mph, holding all other variables constant. This indicator variable was obtained by combining Truckposted60 and Truckposted65 into a single predictor. This was performed for parsimonious reasons, since both Truckposted60 and Truckposted65 had an almost identical effect on the mean speed of trucks at Point 1. The TruckPosted70 indicator coefficient indicates that a posted speed limit of 70 mph is associated with a mean truck operating speed that is 18.055 mph higher than the baseline of a posted speed limit of 35 mph, holding all other variables constant. Overall, the posted speed limit indicator variables show that higher posted speed limits are associated with higher mean operating speeds for trucks at Point 1.

The AdvisoryPresent indicator coefficient indicates that the presence of a reduced speed advisory sign is associated with a mean truck operating speed that is 1.968 mph lower than the baseline condition of no reduced speed advisory sign being present. This finding shows that the presence of an advisory speed sign located before the horizontal curve is decreasing mean truck speeds at Point 1. This variable represents the effect on mean truck operating speed due to the presence of a speed advisory sign, which is required when the advisory speed (necessary to reach proper side friction factors on the horizontal curve) is 10 mph or more below the posted speed limit (FHWA 2012). There has been no previously specified relationship between the presence of an advisory speed warning sign and truck speeds on multilane highways.

The LW coefficient indicates that for every one foot increase in lane width, the mean truck operating speed at Point 1 increases by 2.337 mph. This indicates that as lane width increases, so does the mean truck speed at Point 1. There is no previously established relationship between lane width and truck speed.

The results of the model for mean truck operating speed at Point 2 are shown in Table 17. The model has an R^2_{adj} of 0.572. Independent variables were chosen based on the results of the t-test and the respective significance p-value. The variables selected for this model had a p-value of less than 0.3 and a coefficient that was logical in both sign and magnitude. The Ramsey RESET test is statistically significant (p-value of < 0.0001 is less than $\alpha=0.05$); therefore, it can be concluded that the model has omitted variables. No variable set in the collected data was able to conclude H_o for mean truck speeds at Point 2. This will be further addressed in the recommendations section of this thesis. The Durbin-Watson statistic is $1.609 < d_L = 1.686$ (lower limit for $K = 8$ independent variables); therefore, the null hypothesis can be rejected and it can be concluded that the data contain negative serial correlation. A graph of the residuals versus the observation order, which is displayed in Figure 14 shows that there is a pattern in the residuals. Figure 15 displays a histogram of the residuals for this model and Figure 16 displays a normal probability plot of the residuals for this model. As shown in these graphics, the residuals appear to deviate from normality. This is confirmed in a graph of the residuals versus the fitted values, which is shown in Figure 17. These graphics display heteroskedasticity among the residuals, with the variance decreasing as the fitted values increase. The Breusch-Pagan test for heteroskedasticity was statistically significant (p-value of < 0.0001 is less than $\alpha=0.05$); therefore, the null hypothesis that the residuals are homoskedastic (i.e., have constant variance among all observations) is rejected. The assumption of endogeneity will also be addressed in the systems of equations modeling.

Violating the assumptions of no omitted variables, no serial correlation, and constant variance of the residuals produces biased regression coefficients and inefficient standard errors, which may lead to incorrect model interpretation. These OLS assumption violations for this model are addressed below.

Variable	**Coefficient (β)**	**Standard Error**	**t-statistic**	**p-value**
Constant	21.609	12.350	1.75	0.080
InverseRadius (feet)	-7419.752	1179.606	-6.29	< 0.001
PercentGrade (%)	-1.586	0.059	-26.67	< 0.001
TruckPosted5055 Indicator (1 if car posted speed limit is 50 or 55 mph for trucks; 0 otherwise)*	2.369	1.766	1.34	0.180
TruckPosted6065 Indicator (1 if car posted speed limit is 60 or 65 mph for trucks; 0 otherwise)*	11.400	1.761	6.47	< 0.001
TruckPosted70 Indicator (1 if car posted speed limit is 70 mph for trucks; 0 otherwise)*	17.177	1.943	8.84	< 0.001
AdvisoryPresent (1 if advisory speed sign is present; 0 otherwise)	-3.002	0.895	-3.36	0.001
LW (ft)	2.209	0.929	2.38	0.018
*The baseline is a car posted speed limit of 35 mph. A positive value for the TruckPosted5055, TruckPosted6065, and TruckPosted70 indicator variables shows that mean passenger car operating speeds at Point 2 are higher on roadways with posted speed limits of 50, 55, 60, 65, and 70 mph, when compared to the baseline.				
N	1042			
R^2_{Adj}	0.572			
Root MSE	7.057			

Table 17 – OLS Mean Speed Prediction Model for Trucks at Point 2

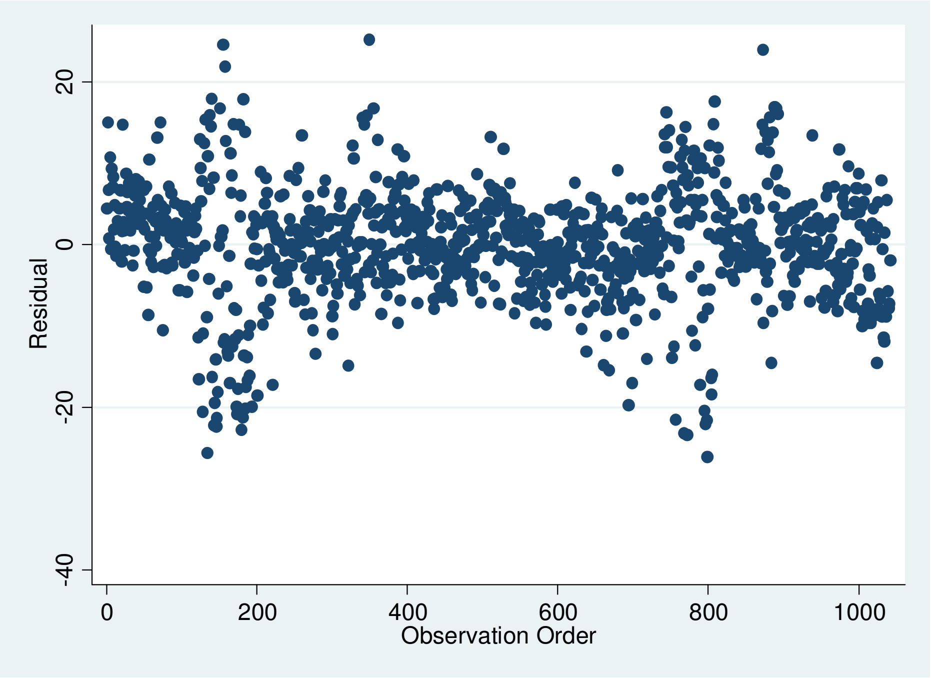


Figure 14 – Residuals vs. Observation Order Plot for Mean Truck Speed at Point 2

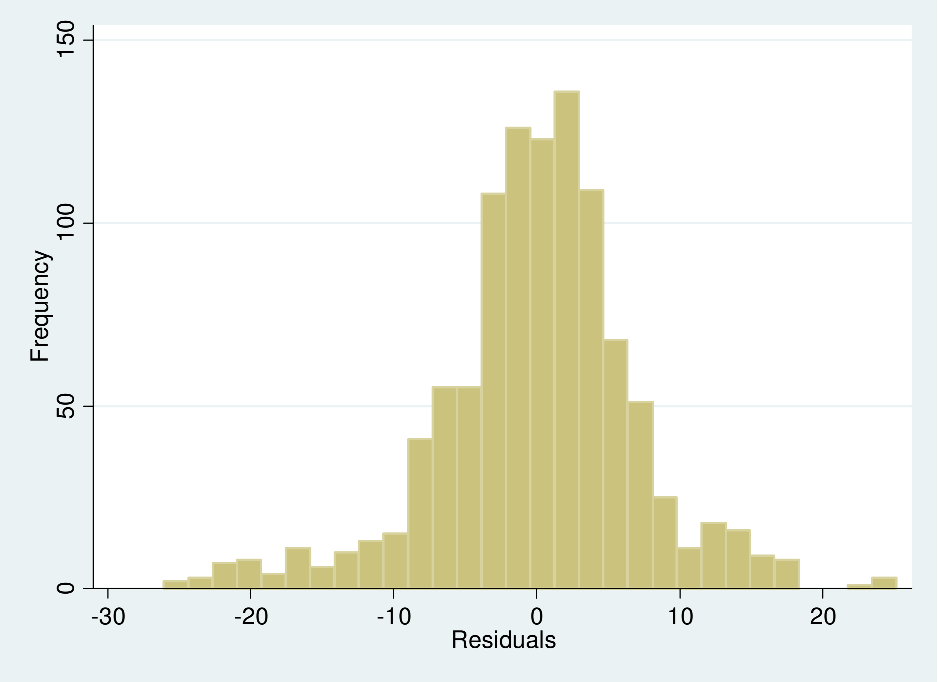


Figure 15 – Histogram of Residuals for Mean Trucks Speed at Point 2

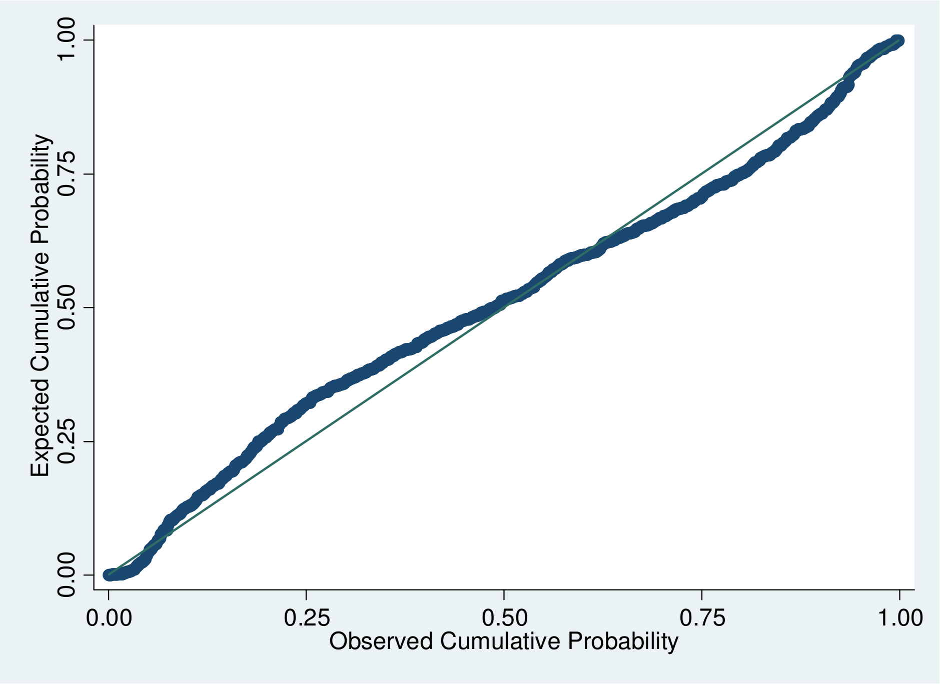


Figure 16 – Normal Probability Plot of Residuals for Mean Truck Speed at Point 2

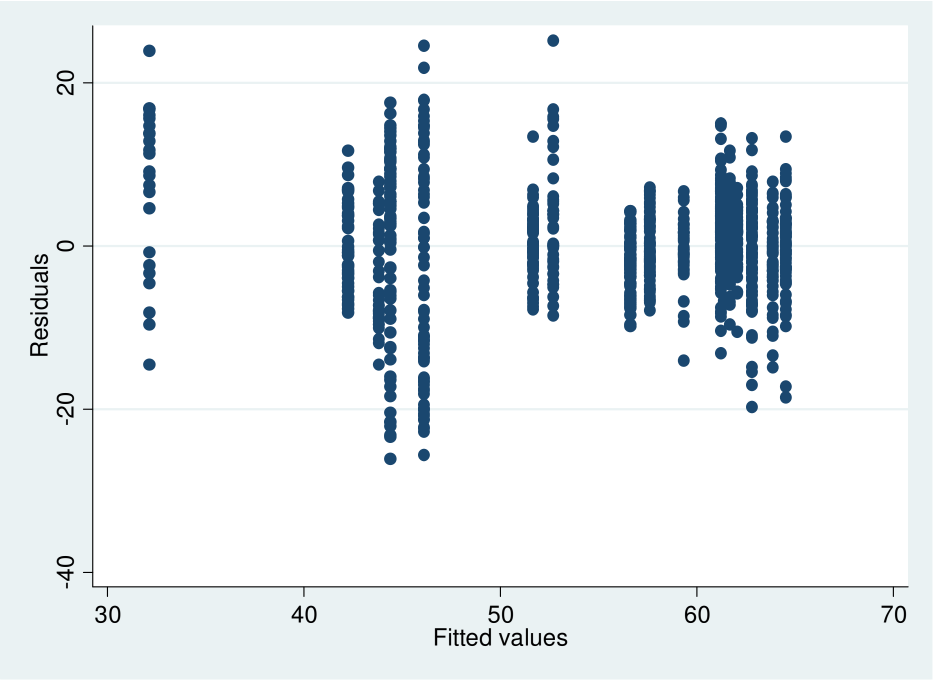


Figure 17 – Residuals vs. Fitted Values Plot for Mean Truck Speed at Point 2

The assumption tests for the OLS model for trucks at Point 2 indicate that there is a time-series factor within the residuals. This violates the OLS assumption of no serial correlation among the disturbance terms. An inspection of the residual versus observation order plot in Figure 18 shows that the residual values do contain correlation; however, this only occurs in segments. This illustrates that the serial correlation is occurring due to the fact that the data are ordered according to site. Therefore, the residual values are correlated based on the variance in the observed speeds at each site. This is exacerbated by the fact that there are only 19 unique sites in the data set. It can be concluded that the serial correlation is limited to specific sections of the data, and not contained in the overall data set for truck speeds at Point 2. Even though this will cause inefficient standard errors, it will not affect the parameter coefficients.

The assumption tests for the OLS model for trucks at Point 2 indicate that there is heteroskedasticity among the residuals. This violates the OLS assumption of equal variance among the disturbances terms. An inspection of the residual versus fitted value plot shows that the variance decreases as the fitted values increase. At sites in which the OLS model predicts a relatively low speed, the variance in the fitted value is higher than sites in which the model predicts a relatively high speed. This disparity is most likely caused by the three sites (WA5, WA7, and MD2) in the data set that contain a positive grade. Table 18 displays descriptive statistics for the speed data from Table 37 in Appendix A, but with these three sites separated from the rest. As shown, average mean truck speed at Point 2 for the three sites with a positive grade is 14.9 mph less than the sites containing a negative grade. This indicates that sites with positive grades contain smaller fitted values. More importantly, the average truck speed standard deviation at

Point 2 for the three sites with a positive grade is 6.99 mph greater than the sites containing a negative grade. This indicates that the variance of the speeds observed at the sites with positive grades is much higher than the sites with negative grades. This is most likely due to the inconsistency in the weight-to-horsepower ratio of fully loaded trucks versus empty trucks observed at these sites. It can be concluded that the heteroskedasticity in the residuals of the OLS model for mean truck speed at Point 2 is caused by the large speed variance at sites with positive grades. This may cause independent variables to be incorrectly omitted or included in the model. However, this will be mostly accounted for by the use of a relaxed p-value for the models in this thesis.

Negative Grade			**Positive Grade**		
Site	**Mean**	**Std Dev**	**Site**	**Mean**	**Std Dev**
WA1	63.00	3.49	WA5	45.20	11.38
WA2	60.44	4.32	WA7	39.55	10.06
WA3	59.00	5.98	MD2	42.15	13.74
WA4	58.83	4.15	**Average**	**42.30**	**11.73**
WA6	61.65	2.83			
CA1	52.10	3.79			
CA2	42.25	5.37			
CA3	39.67	6.10			
WV1	62.45	4.96			
WV2	55.65	7.31			
WV3	63.16	4.77			
WV4	57.25	3.85			
WV5	65.37	4.26			
MD1	62.76	3.48			
MD3	64.32	5.36			
PA2	65.06	4.60			
Average	**58.31**	**4.66**			

Table 18 – Descriptive Statistics for Sites with Positive and Negative Percent Grades at Point 2

The InverseRadius coefficient indicates that for every one foot increase in the inverse of the radius of horizontal curve, the mean passenger car operating speed at Point 2 will decrease by 1/7419.752 mph, holding all other variables constant. In other words, as the radius of the horizontal curve decreases, mean truck speeds will also decrease. This supports previous research that horizontal curve radius and mean truck speed have a direct relationship (Donnell et al. 2001). This coefficient represents the effect of the radius on the truck's ability to transverse a horizontal curve while maintaining enough side friction supply to prevent skidding or rollovers (Harwood et al. 2003).

The PercentGrade coefficient indicates that for every one percent increase in percent of grade at the PC of a horizontal curve, mean truck operating speeds at Point 2 will decrease by 1.586 mph, holding all other variables constant. This supports previous research that grade and truck operating speed are negatively associated (Donnell et al. 2001). Negative grades (downgrades) cause mean truck speeds to increase due to an increase in kinetic energy that cannot be fully absorbed through breaking or engine drag. Positive grades (upgrades) decrease mean truck speeds due to the limitations on the truck's weight-to-horsepower ratio to counteract gravitational acceleration (Harwood et al. 2003).

The TruckPosted5055 indicator coefficient indicates that a posted speed limit of 50 mph or 55 mph is associated with a mean truck operating speed that is 2.369 mph higher than the baseline posted speed limit of 35 mph, holding all other variables constant. This indicator variable was obtained by combining Truckposted50 and Truckposted55 into a single predictor. This was performed for parsimonious reasons, since both Truckposted50 and Truckposted55 had an almost identical effect on the mean speed of trucks at Point 2. The TruckPosted6065 indicator coefficient indicates that a posted speed limit of 60 mph or 65 mph is associated with a mean truck operating speed that is 11.4 mph higher than the baseline posted speed limit of 35 mph, holding all other variables constant. This indicator variable was obtained by combining Truckposted60 and Truckposted65 into a single predictor. This was performed for parsimonious reasons, since both Truckposted60 and Truckposted65 had an almost identical effect on the mean speed of trucks at Point 2. The TruckPosted70 indicator coefficient indicates that a posted speed limit of 70 mph is associated with a mean truck operating speed that 17.177 mph higher than the baseline of posted speed limit of 35 mph, holding all other variables constant. Overall, the posted speed limit indicator variables show that higher posted speed limits are associated with higher mean operating speeds for trucks at Point 2.

The AdvisoryPresent indicator coefficient indicates that the presence of a reduced speed advisory sign is associated with a mean truck operating speed that is 3.002 mph lower than the baseline condition of no reduced speed advisory sign being present. This indicates that the presence of an advisory speed sign located before the horizontal curve is decreasing mean truck speed at Point 2. This variable represents the effect on mean truck operating speed due to a speed advisory sign, which is required when the advisory speed (necessary to reach proper side friction factors on the horizontal curve) is 10 mph or more below the posted speed limit (FHWA 2012).

The LW coefficient indicates that for every one foot increase in the lane width, the mean truck operating speed at Point 2 increases by 2.209 mph. This indicates that as lane width increases, so does the mean truck speed at Point 2.

OLS Regression – Disaggregate Data

In order to run a 3SLS regression with passenger car speeds and truck speeds as the endogenous variables, it was necessary to aggregate the data so that there were an equal number of observed passenger car speeds and truck speeds. This was performed by dividing the speed observations at each site into five ‘parts’ and calculating the mean for each of the ‘parts.’ This then produced 95 individual speed observations for both passenger cars and trucks. Therefore, each average passenger car speed can be entered as an independent variable for the average truck speed (and likewise, each average truck speed can be entered as an independent variable for the average passenger car speed) to check the endogeneity assumption.

It was necessary to develop OLS models for the aggregate data set in order to compare the parameter estimates to the disaggregate data. The average passenger car speeds and average truck speeds were added as independent variables to observe whether or not it is necessary to enter them as an instrumented variable in a 3SLS approach. Table 19 displays descriptive statistics for the aggregate data set. The table includes the mean, standard deviation, minimum, and maximum values for each variable. ‘Speed300’ is the mean passenger car speed at Point 1, ‘SpeedPC’ is the mean passenger car speed at Point 2, ‘TSpeed300’ is the mean truck speed at Point 1, and ‘TSpeedPC’ is the mean truck speed at Point 2. As shown, the mean passenger car speeds are higher than the mean truck speeds at both points. The standard deviations of the truck speeds are higher than the standard deviations of the passenger car speeds at both points.

Variable	Mean	Std Dev	Min	Max
Speed300	64.4	5.7	49.5	72.8
SpeedPC	64.0	6.2	49.5	72.8
TSpeed300	55.8	8.7	34.8	66.5
TSpeedPC	55.3	9.1	34.7	66.7

Table 19 – Descriptive Statistics for Aggregate Speeds

Speed Models at Point 1

The results of the OLS regression model using aggregate data for mean operating speed at Point 1 for passenger cars are shown in Table 20. The model had an R^2_{adj} of 0.878. Independent variables were chosen based on the results of the t-test and the respective p-value. The variables selected for this model had a p-value of less than 0.3 and a coefficient that was logical in both sign and magnitude.

Variable	Coefficient (β)	Standard Error	t-statistic	p-value
Constant	48.592	3.318	14.64	< 0.001
InverseRadius (ft)	-5777.200	1164.328	-4.960	< 0.001
PercentGrade (%)	-0.335	0.105	-3.18	0.002
CarPosted60 Indicator (1 if car posted speed limit is 60 mph; 0 otherwise)	4.461	1.595	2.80	0.006
CarPosted6570 Indicator (1 if car posted speed limit is 65 or 70 mph; 0 otherwise)	5.274	1.625	3.25	0.002
Super (%)	0.379	0.135	2.81	0.006
RsWidth (ft)	0.547	0.177	3.09	0.003
CurveRight Indicator (1 if horizontal curve is to the right; 0 otherwise)	1.680	0.447	3.76	< 0.001
TSpeed300 (mph)	0.116	0.056	2.08	0.040
N	95			
R^2_{Adj}	0.878			
Root MSE	2.005			

Table 20 – OLS Mean Speed Prediction Model for Passenger Cars at Point 1 using Aggregate Data

Most of the variables from the disaggregate data are still statistically significant in the OLS model estimated using the aggregate data. There are a few exceptions, however. The variable RsWidth is now statistically significant, and indicates that for every one foot increase in the right shoulder width, mean passenger car speeds will increase by 0.547 mph at Point 1, holding all other variables constant. The CurveRight indicator variable is now statistically significant, and indicates that the mean passenger car speed on a horizontal curve to the right will be 0.547 mph higher than the baseline condition of a horizontal curve to the left at Point 1, holding all other variables constant. The variable Super is now statistically significant, and indicates that for every one percent increase in superelevation, the mean passenger car speeds at Point 1 will increase by 0.379 mph, holding all other variables constant. This variable is different from the disaggregate OLS model because it no longer contains an inverse transformation. The variable CarPosted6570 indicates that a posted speed limit of 65 or 70 mph will result in a mean passenger car speed that is 5.274 mph higher than the baseline condition of a posted speed limit of 55 mph at Point 1, holding all other variables constant. This variable was formed by combining the variables CarPosted65 and CarPosted70 due to approximately equal magnitudes of effect on the dependent variable. The variable TSpeed300 indicates that for every one mph increase in the mean truck speed, the mean passenger car speed will increase by 0.166 mph at Point 1, holding all other variables constant. This indicates that the mean passenger car speed at Point 1 may contain an endogenous relationship with mean the mean truck speed at Point 1. This will be investigated further in the full 3SLS model.

The results of the OLS model using aggregate data for mean operating speed at Point 1 for trucks is shown in Table 21. The model had an R^2_{adj} of 0.901. Independent variables were chosen based on the results of the t-test and the respective p-value. The variables selected for this model had a p-value of less than 0.3 and a coefficient that was logical in both sign and magnitude.

Variable	Coefficient (β)	Standard Error	t-statistic	p-value
Constant	-10.665	14.773	-0.72	0.472
InverseRadius (ft)	-5032.240	1307.548	-3.850	< 0.001
PercentGrade (%)	-1.302	0.113	-11.50	< 0.001
TruckPosted55 Indicator (1 if truck posted speed limit is 55 mph for trucks; 0 otherwise)	2.664	1.645	1.62	0.109
TruckPosted6070 Indicator (1 if truck posted speed limit is 60, 65, or 70 mph for trucks; 0 otherwise)	12.236	1.202	10.18	< 0.001
CurveRight Indicator (1 if horizontal curve is to the right; 0 otherwise)	-4.351	0.609	-7.14	< 0.001
LW (ft)	3.547	0.933	3.80	< 0.001
Speed300 (mph)	0.259	0.126	2.05	0.043
N	95			
R^2_{Adj}	0.901			
Root MSE	2.740			

Table 21 – OLS Mean Speed Prediction Model for Trucks at Point 1 using Aggregate Data

Most of the variables from the disaggregate data are still statistically significant in the OLS model estimated using the aggregate data. There are a few exceptions, however. The CurveRight indicator variable is now statistically significant, and indicates that the mean truck speed on a horizontal curve to the right will be 4.35 mph lower than the baseline condition of a horizontal curve to the left for Point 1, holding all other variables constant. The variable TruckPosted6070 indicates that a posted speed limit of 60, 65 or 70 mph will result in a mean truck speed that is 12.236 mph higher than the baseline condition of a posted speed limit of 35 mph at Point 1, holding all other variables constant. This variable was formed by combining the variables TruckPosted60, TruckPosted65, and TruckPosted70 due to approximately equal magnitudes of effect on the dependent variable. TruckPosted50 no longer had a significant effect on the mean truck speed over the baseline at Point1. Speed300 indicates that for every one mph increase in the mean passenger car speed, the mean truck speed will increase by 0.259 mph at Point 1, holding all other variables constant. This indicates that the mean truck speed at Point 1 may contain an endogenous relationship with mean the mean passenger speed at Point 1. This will be investigated further in the full 3SLS model.

Speed Models at Point 2

The results of the OLS model using aggregate data for mean operating speed at Point 2 for passenger cars is shown in Table 22. The model had an R^2_{adj} of 0.882. Independent variables were chosen based on the results of the t-test and the respective p-value. The variables selected for this model had a p-value of less than 0.3 and a coefficient that was logical in both sign and magnitude.

Variable	Coefficient (β)	Standard Error	t-statistic	p-value
Constant	50.493	3.349	15.08	< 0.001
InverseRadius (ft)	-8105.626	1111.141	-7.290	< 0.001
PercentGrade (%)	-0.323	0.105	-3.07	0.003
CarPosted6070 Indicator (1 if car posted speed limit is 60, 65, or 70 mph; 0 otherwise)	3.572	1.607	2.22	0.029
Super (%)	0.469	0.139	3.39	0.001
RsWidth (ft)	0.391	0.184	2.13	0.036
CurveRight Indicator (1 if horizontal curve is to the right; 0 otherwise)	1.744	0.465	3.75	< 0.001
TSpeedPC(mph)	0.148	0.056	2.65	0.010
N	95			
R^2_{Adj}	0.882			
Root MSE	2.085			

Table 22 – OLS Mean Speed Prediction Model for Passenger Cars at Point 2 using Aggregate Data

Most of the variables from the disaggregate data are still statistically significant in the OLS model estimated using the aggregate data. There are a few exceptions, however. The variable RsWidth is now statistically significant, and indicates that for every one foot increase in the right shoulder width, mean passenger car speeds will increase by 0.391 mph at Point 2, holding all other variables constant. The CurveRight indicator variable is now statistically significant, and indicates that the mean passenger car speed on a horizontal curve to the right will be 4.35 mph lower than the baseline condition of a horizontal curve to the left for Point 2, holding all other variables constant. The variable CarPosted6070 indicates that a posted speed limit of 60, 65, or 70 mph will result in a mean passenger car speed that is 3.572 mph higher than the baseline condition of a posted speed limit of 55 mph at Point 2, holding all other variables constant. This variable was formed by combining the variables CarPosted60, CarPosted65, and CarPosted70 due to approximately equal magnitudes of effect on the dependent variable. The variable

TSpeedPC indicates that for every one mph increase in the mean truck speed, the mean passenger car speed will increase by 0.056 mph at Point 2, holding all other variables constant. This indicates that the mean passenger car speed at Point 2 may contain an endogenous relationship with mean the mean truck speed at Point 2. This will be investigated further in the full 3SLS model.

The results of the OLS model using aggregate data for mean operating speed at Point 2 for trucks is shown in Table 23. The model had an R^2_{adj} of 0.902. Independent variables were chosen based on the results of the t-test and the respective p-value. The variables selected for this model had a p-value of less than 0.3 and a coefficient that was logical in both sign and magnitude.

Variable	**Coefficient (β)**	**Standard Error**	**t-statistic**	**p-value**
Constant	-10.939	14.438	-0.76	0.451
InverseRadius (ft)	-5399.645	1443.168	-3.740	0.000
PercentGrade (%)	-1.320	0.118	-11.18	0.000
TruckPosted55 Indicator (1 if car posted speed limit is 55 mph for trucks; 0 otherwise)	2.102	1.663	1.26	0.209
TruckPosted6070 Indicator (1 if car posted speed limit is 60, 65, or 70 mph for trucks; 0 otherwise)	12.187	1.223	9.97	0.000
CurveRight Indicator (1 if horizontal curve is to the right; 0 otherwise)	-4.395	0.622	-7.06	0.000
LW (ft)	3.503	0.946	3.70	0.000
Speed PC (mph)	0.272	0.127	2.14	0.035
N	95			
R^2_{Adj}	0.905			
Root MSE	2.806			

Table 23– OLS Mean Speed Prediction Model for Trucks at Point 2 using Aggregate Data

Most of the variables from the disaggregate data are still statistically significant in the OLS model estimated using the aggregate data. There are a few exceptions, however. The CurveRight indicator variable is now statistically significant, and indicates that the mean truck speed on a horizontal curve to the right will be 4.395 mph lower than the baseline condition of a horizontal curve to the left at Point 2, holding all other variables constant. The variable TruckPosted6070 indicates that a posted speed limit of 60, 65 or 70 mph will result in a mean truck speed that is 12.187 mph higher than the baseline condition of a posted speed limit of 35 mph at Point 2, holding all other variables constant. This variable was formed by combining the variables TruckPosted60, TruckPosted65, and TruckPosted70 due to approximately equal magnitudes of effect on the dependent variable. TruckPosted50 no longer had a significant effect on the mean truck speed over the baseline at Point 2. Speed300 indicates that for every one mph increase in the mean passenger car speed, the mean truck speed will increase by 0.127 mph at Point 2, holding all other variables constant. This specifies that the mean truck speed at Point 2 may contain an endogenous relationship with mean the mean passenger speed at Point 2. This will be investigated further in the full 3SLS model.

3SLS Regression

A 3SLS regression model was developed for Point 1 and Point 2 in order to account for the potential endogenous relationship between passenger car and truck speeds. The structural equations were developed using the independent variables found to be statistically significant in the respective aggregate OLS models in the previous section. The 3SLS models used mean truck speed and mean passenger car speed as the only endogenous variables. All other independent variables were classified as exogenous variables. These models can be compared to the disaggregate OLS models to determine if the assumption of endogeneity is violated. It is worth noting that although the 3SLS models predict the mean passenger car and mean truck speeds, they cannot be transformed into an equation form used for future prediction. This is due to the fact that the endogenous variables are products of the speeds collected for this particular dataset, and cannot be repeated in future measurements. These speed prediction models do, however, attempt to illustrate the effects of certain geometric and roadway characteristic parameters by utilizing a statistical modeling technique that generates more efficient parameter estimates by accounting for variable endogeneity.

Speed Models at Point 1

The reduced form parameter estimates of the 3SLS regression for the mean passenger car speed and mean truck speed at Point 1 are displayed in Table 24. These parameter estimates were used to form the instrumented estimate for their respective endogenous variable. Therefore, the signs and magnitudes from these estimates may differ considerably from the structural form parameter estimates.

Variable	Speed300	TSpeed300
Constant	48.310	17.901
InverseRadius (ft)	-7371.995	-3727.411
PercentGrade (%)	-0.466	-1.642
CarPosted60 Indicator (1 if car posted speed limit is 60 mph; 0 otherwise)	3.257	9.544
CarPosted6570 Indicator (1 if car posted speed limit is 65 or 70 mph; 0 otherwise)	3.757	10.442
Super (%)	0.6409	-0.4943
RsWidth (ft)	0.663	-0.769
CurveRight Indicator (1 if horizontal curve is to the right; 0 otherwise)	1.384	-4.266
TruckPosted55 Indicator (1 if car posted speed limit is 55 mph for trucks; 0 otherwise)	4.136	-2.356
TruckPosted6070 Indicator (1 if car posted speed limit is 60, 65, or 70 mph for trucks; 0 otherwise)	2.544	10.297
LW (ft)	0.329	2.638

Table 24 – 3SLS Reduced Form Parameter Estimates at Point 1

The structural form results of the full 3SLS model using aggregate data for mean operating speed at Point 1 for passenger cars and trucks are shown in Table 25. Equation 1 displays the structural form estimates for the dependent variable Speed300. Equation 2 displays the structural form estimates for the dependent variable TSpeed300. The equations had an R^2_{adj} value of 0.888 and 0.909, respectively. As shown, all variables that were significant in the respective OLS models using the aggregate data in Table 20 and Table 21 are still significant in the 3SLS model. The p-values for the endogenous independent variables Speed300 and TSpeed300 were increased considerably; however, with values of 0.254 and 0.245, respectively, they were still below the level of significance used for this thesis. Therefore, it can be concluded that endogeneity may exist between mean passenger car speeds and mean truck speeds at Point 1.

Equation 1 (Speed300)				
Variable	**Coefficient (β)**	**Standard Error**	**t-statistic**	**p-value**
Constant	50.238	3.680	13.65	< 0.001
InverseRadius (ft)	-5801.376	1138.656	-5.090	< 0.001
PercentGrade (%)	-0.401	0.119	-3.37	0.001
CarPosted60 Indicator (1 if car posted speed limit is 60 mph; 0 otherwise)	5.645	1.687	3.35	0.001
CarPosted6570 Indicator (1 if car posted speed limit is 65 or 70 mph; 0 otherwise)	6.451	1.694	3.81	< 0.001
Super (%)	0.3681	0.129	2.85	0.004
RsWidth (ft)	0.470	0.167	2.81	0.005
CurveRight	1.599	0.432	3.70	0.000
TSpeed300 (mph)	0.079	0.069	1.14	0.254
Equation 2 (TSpeed300)				
Variable	**Coefficient (β)**	**Standard Error**	**t-statistic**	**p-value**
Constant	-10.298	19.682	-0.52	0.601
InverseRadius (ft)	-4979.734	1969.353	-2.530	0.011
PercentGrade (%)	-1.311	0.158	-8.33	< 0.001
TruckPosted55 Indicator (1 if truck posted speed limit is 55 mph for trucks; 0 otherwise)	3.088	1.626	1.90	0.058
TruckPosted6070 Indicator (1 if truck posted speed limit is 60, 65, or 70 mph for trucks; 0 otherwise)	12.433	1.444	8.61	< 0.001
CurveRight Indicator (1 if horizontal curve is to the right; 0 otherwise)	-4.333	0.593	-7.31	< 0.001
LW (ft)	3.522	0.900	3.91	< 0.001
Speed300 (mph)	0.254	0.218	1.16	0.245

Equation	**1**	**2**
N	95	95
R^2_{Adj}	0.888	0.909
Root MSE	1.915	2.630

Table 25 – 3SLS Estimates for Mean Passenger Cars and Mean Trucks at Point 1

Speed Models at Point 2

The reduced form parameter estimates of the 3SLS regression for the mean passenger car speed and mean truck speed at Point 2 are displayed in Table 26. These parameter estimates were used to form the instrumented estimate for their respective endogenous variable. Therefore, the signs and magnitudes from these estimates may differ considerably from the structural form parameter estimates.

Variable	**SpeedPC**	**TSpeedPC**
Constant	48.845	23.365
InverseRadius (ft)	-9714.914	-6291.143
PercentGrade (%)	-0.507	-1.664
CarPosted6070 Indicator (1 if car posted speed limit is 60, 65, or 70 mph; 0 otherwise)	2.696	8.977
Super (%)	0.685	-0.327
RsWidth (ft)	0.458	-0.935
CurveRight Indicator (1 if horizontal curve is to the right; 0 otherwise)	1.227	-4.363
TruckPosted55 Indicator (1 if car posted speed limit is 55 mph for trucks; 0 otherwise)	3.578	-2.196
TruckPosted6070 Indicator (1 if car posted speed limit is 60, 65, or 70 mph for trucks; 0 otherwise)	2.890	10.589
LW (ft)	0.588	2.418

Table 26 – 3SLS Reduced Form Parameter Estimates at Point 2

The results of the full 3SLS model using aggregate data for mean operating speed at Point 2 for passenger cars and trucks are shown in Table 27. Equation 1 displays the structural form estimates for the dependent variable SpeedPC. Equation 2 displays the structural form estimates for the dependent variable TSpeedPC. The equations had an R^2_{adj} value of 0.896 and 0.912, respectively. As shown, all variables that were significant in the respective OLS models with the aggregate data in Table 22 and Table 23 are still statistically significant. The p-values for the endogenous independent variables SpeedPC and TSpeedPC were increased; however, with values of 0.078 and 0.238, respectively, they were still below the level of significance used for this thesis. Therefore, it can be concluded that endogeneity may exist between mean passenger car speeds and mean truck speeds at Point 2.

Equation 1 (SpeedPC)				
Variable	**Coefficient (β)**	**Standard Error**	**t-statistic**	**p-value**
Constant	51.941	3.726	13.94	< 0.001
InverseRadius (ft)	-8143.981	1104.808	-7.370	< 0.001
PercentGrade (%)	-0.374	0.119	-3.15	0.002
CarPosted6070 Indicator (1 if car posted speed limit is 60, 65, or 70 mph; 0 otherwise)	4.681	1.684	2.78	0.005
Super (%)	0.458	0.134	3.43	0.001
RsWidth (ft)	0.275	0.174	1.59	0.113
CurveRight Indicator (1 if horizontal curve is to the right; 0 otherwise)	1.657	0.452	3.67	< 0.001
TSpeedPC (mph)	0.123	0.070	1.76	0.078
Equation 2 (TSpeedPC)				
Variable	**Coefficient (β)**	**Standard Error**	**t-statistic**	**p-value**
Constant	-12.765	20.249	-0.63	0.528
InverseRadius (ft)	-5077.708	2487.855	-2.040	0.041
PercentGrade (%)	-1.311	0.184	-7.14	< 0.001
TruckPosted55 Indicator (1 if truck posted speed limit is 55 mph for trucks; 0 otherwise)	2.521	1.609	1.57	0.117
TruckPosted6070 Indicator (1 if truck posted speed limit is 60, 65, or 70 mph for trucks; 0 otherwise)	12.267	1.567	7.83	< 0.001
CurveRight Indicator (1 if horizontal curve is to the right; 0 otherwise)	-4.393	0.608	-7.23	< 0.001
LW (ft)	3.507	0.894	3.92	< 0.001
SpeedPC (mph)	0.295	0.250	1.18	0.238

Equation	**1**	**2**
N	95	95
R^2_{Adj}	0.896	0.912
Root MSE	2.003	2.687

Table 27 – 3SLS Estimates for Mean Passenger Cars and Mean Trucks at Point 2

Chapter 7. DISCUSSION

The following chapter focuses on information that can be drawn from the models presented in the previous chapter. Each of the models that were developed contained parameter estimates that were logical and as expected. However, in comparing the models and variables to themselves and each other, a few interesting inferences and patterns arise. The four OLS models are first compared to each other to examine the influence of each predictor variable on speed. The different modeling techniques are then compared in order to observe how each performs in predicting mean speeds.

OLS Model Discussion

The OLS models that were developed can be transformed into linear equations. These equations can be used to predict mean speeds when inputting geometric data or roadway characteristics. The equations that resulted from the models presented in this thesis are shown in Table 28.

Car (-300)	$V_{avg} = 64.132 - \frac{7210.68}{R} - 0.399G - \frac{7.235}{e} + 5.183CPL_{60} + 6.744CPL_{65} + 7.383CPL_{70}$
Car (PC)	$V_{avg} = 45.059 - \frac{6319.59}{R} - 0.431G - \frac{8.228}{e} + 1.573LW - 2.698AP + 6.04CPL_{60-65} + 8.83CPL_{70}$
Truck (-300)	$V_{avg} = 17.861 - \frac{6564.19}{R} - 1.527G + 2.337LW - 1.968AP + 3.537TPL_{50} + 5.619TPL_{55} + 13.343TPL_{60-65} + 18.055TPL_{70}$
Truck (PC)	$V_{avg} = 21.609 - \frac{7419.752}{R} - 1.586G + 2.209LW - 3.002AP + 2.369TPL_{50-55} + 11.4TPL_{60-65} + 17.177TPL_{70}$

Where:

-300	300 feet before the PC
PC	Point of Curvature
V_{avg}	Average (mean) speed (mph)
R	Radius of horizontal curve (ft)
G	Grade of the approach tangent (%)
e	Superelevation (%)
LW	Lane width (ft)
AP	Presence of an Advisory Speed Sign (1 if present; 0 otherwise)
CPL_{60}	Car posted speed limit of 60 mph (1 if present; 0 otherwise)
CPL_{65}	Car posted speed limit of 65 mph (1 if present; 0 otherwise)
CPL_{70}	Car posted speed limit of 70 mph (1 if present; 0 otherwise)
CPL_{60-65}	Car posted speed limit of 60 or 65 mph (1 if present; 0 otherwise)
TPL_{50}	Truck posted speed limit of 50 mph (1 if present; 0 otherwise)
TPL_{55}	Truck posted speed limit of 55 mph (1 if present; 0 otherwise)
TPL_{70}	Truck posted speed limit of 70 mph (1 if present; 0 otherwise)
TPL_{50-55}	Truck posted speed limit of 50 or 55 mph (1 if present; 0 otherwise)
TPL_{60-65}	Truck posted speed limit of 60 or 65 mph (1 if present; 0 otherwise)

Table 28 – OLS Speed Prediction Models

The radius of horizontal curve was statistically significant in all four OLS linear regression models. This was anticipated, since all sites were selected with a sharp horizontal curve as a criterion. Based on the magnitude of the coefficients, horizontal curve radius is expected to decrease mean passenger car speed at Point 1 more so than at Point 2. However, horizontal curve radius has a larger influence in decreasing the mean truck speed at Point 2 than Point 1. One possible reason is that trucks take longer to adjust their speed in order to account for the effects of traversing a horizontal curve (and the required side friction demand) than passenger cars. Figure 22 in Appendix B displays the predicted mean speeds at different curve radii when all other variables are held constant at their mean values. It is clear that mean truck speeds are much lower than passenger car speeds at all horizontal curve radii values. This difference is also consistent over all values of horizontal curve radius, with mean car speeds being approximately 10 mph higher than mean truck speeds. There is an insignificant amount of mean speed difference between Point 1 and Point 2 at all curve radii for both passenger cars and trucks. The speed profiles also appear to have the same trend line, with mean speeds increasing more as curve radius increases at the lower radius values than the higher radius values. This indicates that an increase or decrease in curve radius has a larger effect on mean passenger car and truck speeds for relatively shaper curves than for flatter curves.

The percent grade was statistically significant in all four OLS linear regression models. This was anticipated since sites were selected with a steep grade as one of the criterion. The coefficients for both passenger cars and trucks indicate that the vertical grade has a larger effect on mean operating speed at Point 2 than at Point 1. This is likely due to the fact that the vehicles have been traversing the vertical grade (and subjected to the associated gravitational acceleration) for a longer period of time at point 2 than at point 1. Figure 23 in Appendix B shows the predicted mean speeds at different values of the percent grade when all other variables are held constant at their mean values. This graph shows that the difference between the predicted mean speed at Point 1 and Point 2 is negligible for both passenger cars and trucks. It is clear that a change in percent grade has a larger effect on trucks than passenger cars, with the trend line slope of the predicted mean speed of trucks being much more negative than that of passenger cars. On extreme negative grades (-6% or steeper), the expected mean speed of passenger cars is approximately 5 mph greater. On extreme positive grades (+6% steeper), the predicted mean speed of passenger cars is approximately 20 mph larger than trucks. This signifies that the limiting factor for trucks on upgrades (weight-to horsepower ratio) has a much larger influence on the speed difference than on downgrades.

Lane width was a significant predictor in the passenger car model at Point 2 and in both truck models. The lane width coefficients indicate that lane width has a larger effect on mean truck speed at Point 1 than at Point 2. This difference appears to be negligible in Figure 24 in Appendix B, which displays the expected mean speeds at different lane width values. This figure shows that a change in lane width does affect mean truck speed more than mean passenger car speed, with the slope of each mean truck speed line being more positive than the mean passenger car speed. On highways with smaller lane widths (9 ft), the mean passenger car speed is approximately 11 mph larger than the mean truck speed. Similarly, on highways with larger lane widths (12.5 ft), the mean passenger car speed is approximately 8 mph larger than the mean truck speed. This indicates that a decrease in lane width more significantly influences a truck's ability to traverse a horizontal curve on a steep grade than passenger cars. Lane width was not significant in the passenger car model at Point 1. This is probably due to the fact that lane width does not become a contributing factor to passenger car speed until the passenger car reaches the horizontal curve.

Superelevation was a significant predictor in both passenger car models. This is intuitive since superelevation counteracts the limiting factor for passenger car speeds on a horizontal curve (discomfort caused from lateral acceleration). This also signifies that although superelevation scales with minimum horizontal curve radius requirements in design, it still contains enough variability in field measurements to significantly influence mean passenger car speed (AASHTO 2004). Superelevation was not significant in the either of the truck models at Point 1 or Point 2. This may be attributed to the fact that trucks do not reach the levels of lateral acceleration that passenger cars attain, which causes driver discomfort. Therefore, the superelevation on the horizontal curve, which acts as a counterbalance to lateral acceleration, does not significantly influence truck speed. Figure 25 in Appendix B displays the mean passenger car speed for different values of superelevation rates. As shown, the effect of changing the superelevation rate has a larger effect on mean passenger car speed for lower values of superelevation rates than higher values. Even though the mean passenger car speed at Point 1 is larger than Point 2, the effect of changing the superelevation rate is no different between the two points.

The presence of an advisory speed warning sign was statistically significant in the passenger car model at Point 2 and in both truck models. The coefficients for this variable indicate that the presence of an advisory speed sign has a larger effect on truck speeds than passenger car speeds at Point 2. It also had a larger effect on truck speeds at Point 2 than at Point 1. This indicates that speed advisory warning signs cause drivers to slow while entering horizontal curves. Since this variable was not significant for passenger cars at Point 1, it also indicates that when this speed advisory sign is present, truck drivers tend to adjust their speed at a point further from the curve than passenger car drivers. This variable was not significant in the passenger car speed model at Point 1. This may be due to the fact that Point 1 is located on the tangent. Therefore, a speed advisory sign does not cause passenger cars to adjust their speed until they reach the horizontal curve.

Posted speed limit indicators were significant in all four OLS linear regression models. This was expected since data were recorded on multilane highways with different posted speed limits. The coefficients of every posted speed limit were positive in sign. This is intuitive since the baseline posted speed limit was lower than every posted speed limit indicator in the models. The coefficients of every speed limit were either the same or higher than antecedent posted speed limit indicators in the models. This indicates that the regulatory speed limit on a highway facility directly influences mean passenger car and truck speeds.

The OLS linear regression equations displayed in Table 28 can also be compared to OLS linear regression model equations developed in previous research. Table 29 displays all previously developed OLS equations for passenger cars on multilane highways that contain independent variables that were also present in the passenger car models developed in this thesis. Table 30 displays all previously developed OLS equations for trucks that contain independent variables that were also present in the truck models developed in this thesis. These comparisons show that the OLS speed prediction models developed in this thesis comprise of key similarities and differences from speed prediction models that have been developed in past research.

Author	Location	Model	R^2
Fitzpatrick et al. (1997)		$V85_{curve} = 56.34 + 0.808R^{0.5} + 9.34/AD$	
Poe and Mason (2000)	PC150	$V_{avg} = 49.59 + 0.5(DEGCVR) - 0.35(GRADE) + 0.74(LNWIDN) - 0.74(HZRT5M)$	
	PC	$V_{avg} = 51.13 - 0.1(DEGCVR) - 0.24(GRADE) - 0.01(LNWIDN) - 0.57(HZRT5M)$	
Figueroa and Tarko (2004)		$V_p = 54.027 - 4.764 * PSL_{50} - 4.942 * PSL_{45} - 6.509 * PSL_{40} + 1.652 * RUR + 1.281x10^{-3} * SD - 0.320 * INTD + 0.034 * ECLR + 0.056 * ICLR + 5.899 * Z_p - 0.423 * \left(Z_p * PSL_{45-40}\right) - 0.464 * \left(Z_p * RUR\right) - 4.800x10^{-4} * \left(Z_p * SD\right) + 0.042 * \left(Z_p * INTD\right) - 4.220x10^{-3} * \left(Z_p * CLR\right) - 0.477 * (Z_p * TWLT)$	
Ali et al. (2007)		$FFS_{Mean} = 37.4 + 6.8PS_{45} + 2.6PS_{40} + 13.5SL$	0.87
Gong and Stamatiadis (2008)	Inside Lane	$V_{85} = 51.520 + 1.567 * ST - 2.795 * MT - 4.001 * PT - 2.150 * AG + 2.221 * \ln(LC)$	0.647
	Outside Lane	$V_{85} = 60.779 + 1.804 * ST - 2.251 * MT - 1.071 * AG - 1.519 * FC + 0.000472 * R + 2.408 * \frac{LC}{R}$	0.432

Table 29 – Previously Developed Speed Prediction Models for Passenger Cars

Author	Location	Model	R^2
Donnell et al. (2001)	PC200	$V_{85} = 51.5 + 0.137(R) - 0.779(GAPT) + 0.0127(LAPT) - 0.000119(LATP * R)$	0.662
	PC	$V_{85} = 78.4 + 0.0140(R) - 1.40(GDEP) - 0.00724(LDEP)$	0.562
Adolini and Elafteriadou (2003)	PC200	$V_{avg} = 107 - \frac{8315}{R}$	0.846
	PC	$V_{avg} = 94.7 - \frac{2028}{R} - 1.98G_1 - 0.0140T_1$	0.568

Table 30 – Previously Developed Speed Prediction Models for Trucks

Fitzpatrick et al. (1997) showed a direct relationship between passenger car speed and horizontal curve radius. This is consistent with the OLS models developed in this thesis at Point 1 and Point 2. Both models show that this relationship is defined by a power law not equal to 1, with the Fitzpatrick model having a power of 0.5 and the models in this thesis having a power of -1.

Poe and Mason (2000) developed mean speed prediction equations for the point 250 feet before the PC and at the PC, which are comparable to Point 1 and Point 2 in this thesis. These models show a negative linear relationship between passenger car speed and the approach tangent grade. This is consistent with the OLS models developed in this thesis at Point 1 and Point 2. The magnitude of this relationship is very similar for these two models and the models developed in this thesis for passenger cars. This model contains a coefficient of -0.35 at 250 feet before the PC and the model developed in this thesis contains a coefficient of -0.399 at Point 1. The Poe and Mason (2000) model contains a coefficient of -0.24 at the PC and the model developed in this thesis contains a coefficient of -0.431 at Point 2. These models also show that lane width is a significant predictor for mean passenger car speeds, although the relationship is different at the two points. The Poe and Mason (2000) models show a direct relationship at 250 feet before the PC, but a negative relationship at the PC. The models developed in this thesis illustrate that lane width has a direct relationship at Point 2, but no statistical significance at Point 1.

Figueroa and Tarko (2004) developed a speed prediction model for passenger cars in which the posted speed limit is a significant predictor. With a baseline speed limit of 55 mph in this model, a direct relationship between passenger car speed and posted speed limit is shown. This is consistent with both OLS linear regression models developed in this thesis for passenger cars.

Ali et al. (2007) developed a speed prediction model for passenger cars in which the posted speed limit is a significant predictor. With a baseline speed limit of 35 mph in this model, a direct relationship between passenger car speed and posted speed limit is shown.

This is consistent with both OLS linear regression models developed in this thesis for passenger cars.

Gong and Stamatiadis (2008) developed speed prediction models for passenger cars in which the horizontal curve radius is a significant predictor for the inside and outside lanes. Both of these models show that there is a direct linear relationship between horizontal curve radius and passenger car speed. The direct relationship is consistent with both models in this thesis for passenger cars; however, the models in this thesis show that the relationship is not linear. These models also illustrate that there is an interaction between horizontal curve radius and the length of curve. No such interaction terms were found to be significantly significant in any model in this thesis.

Donnell et al. (2001) developed mean speed prediction models for trucks at the point 100 meters before the PC and at the PC, which are comparable to Point 1 and Point 2 in this thesis. These models show that there is a direct linear relationship between horizontal curve radius and truck speed. The direct relationship is consistent with both of the OLS truck models developed in this thesis; however, the models in this thesis show that the relationship is not linear. These models show a negative linear relationship between truck speed and the approach tangent grade. This is consistent with the OLS models developed in this thesis at Point 1 and Point 2. These models also illustrate that there is a negative relationship between the truck speeds and the grade of the approach tangent. This negative relationship is consistent with both of the OLS truck models developed in this thesis. Although these models predict the 85th percentile truck speeds, the magnitudes of this relationship are very similar to those developed in this thesis. This model contains a coefficient of -1.30 at 100 meters before the PC and the model developed in this thesis contains a coefficient of -1.527 at Point 1. This model contains a coefficient of -1.40 at the PC and the model developed in this thesis contains a coefficient of -1.586 at Point 2. Figures 32 and 33 in Appendix B show the predicted mean speeds at different values of the horizontal curve radius when all other variables are held constant at their mean values for Donnell et al. (2001) at the Point 1 and Point 2 equivalencies. This model is plotted along with the model developed for trucks in this thesis. As shown, the two models appear to be very consistent with the predicted mean speeds for relatively low values of horizontal curve radius at Point 1. The two models appear to be very consistent with the predicted mean speeds for all values of horizontal curve radius at Point 2.

Adolini and Elafteriadou (2003) developed mean speed prediction models for trucks at the point 100 meters before the PC and at the PC, which are comparable to Point 1 and Point 2. These models show that there is a direct relationship between horizontal curve radius and truck speed. Both of these models show that this relationship is defined by a power law not equal to 1, with the power being equal to -1. This is consistent with the relationship developed between truck speeds and horizontal curve radius in the models developed in this thesis at Point1 and Point 2. The magnitude of this inverse relationship is similar for these two models and the models developed in this thesis for trucks. This model contains a coefficient of 1/-7188 at 100 meters before the PC and the model developed in this thesis contains a coefficient of 1/-6564 at Point 1. This model contains a coefficient of 1/-2028 at the PC and the model developed in this thesis contains a coefficient of 1/-7419 at Point 2. These models also display that there is a negative relationship between truck speed and the grade of the approach tangent at the PC, containing a coefficient of -1.98. This is consistent with the OLS truck model developed in this thesis at Point 2, which contains a coefficient of -1.586. Figures 32 and 33 in Appendix B shows the predicted mean speeds at different values of the horizontal curve radius when all other variables are held constant at their mean values for Adolini and Elafteriadou (2003) at the Point 1 and Point 2 equivalencies. This model is plotted along with the model developed for trucks in this thesis. As shown, the two models appear to be very consistent with the predicted mean speeds for all values of horizontal curve radius at both points.

3SLS Model Discussion

A 3SLS Regression analysis was performed at Point 1 and at Point 2 in order to account for the endogeneity between passenger car speeds and truck speeds. It was necessary to compare these models to the OLS models developed in this thesis to assess the validity of using a simultaneous equations approach. Table 31 displays the results for both the OLS model and 3SLS model for passenger cars at Point 1. The tables exhibit a comparison between the parameter coefficient values and standard error of all independent variables, as well as the goodness-of-fit estimates. As shown, the parameter estimates for independent variables that were present in both models are similar. The standard errors, however, are higher for the 3SLS model than the OLS linear regression model. This suggests that OLS linear regression underestimates the standard error of independent variables included in the model when endogenous predictor variables are not considered.

OLS Regression			3SLS Regression		
Variable	**Coef**	**SE**	**Variable**	**Coef**	**SE**
Constant	64.132	41.890	Constant	50.238	3.680
InverseRadius (ft)	-7210.676	651.447	InverseRadius (ft)	-5801.376	1138.656
PercentGrade (%)	-0.399	0.047	PercentGrade (%)	-0.401	0.119
CarPosted60	5.183	0.798	Carposted60	5.645	1.687
CarPosted65	6.744	0.969	Carposted6570	6.451	1.694
CarPosted70	7.383	0.890	Super (%)	0.368	0.129
InverseSuper (%)	-7.235	1.973	RsWidth (ft)	0.470	0.167
N	1509		CurveRight	1.599	0.432
R^2_{Adj}	0.501		TSpeed300 (mph)	0.079	0.069
Root MSE	5.490		**N**	95	
			R^2_{Adj}	0.888	
			Root MSE	1.915	

Table 31 – Comparison of OLS and 3SLS models for Passenger Cars at Point 1

Table 32 displays the results for both the OLS model and 3SLS model for passenger cars at Point 2. The table exhibits a comparison between the parameter coefficients and standard errors of all independent variables, as well as the goodness-of-fit estimates. As shown, the parameter estimates for independent variables that were present in both models are similar. The standard errors, however, are higher for the 3SLS model than the OLS linear regression model. This indicates that, when not accounting for potential endogeneity among truck and passenger car speeds, standard errors for single OLS linear regression models may be underestimated.

OLS Regression			**3SLS Regression**		
Variable	**Coef**	**SE**	**Variable**	**Coef**	**SE**
(Constant)	45.059	8.233	Constant	51.941	3.726
InverseRadius (ft)	-6319.590	1080.725	InverseRadius (ft)	-8143.981	1104.808
PercentGrade (%)	-0.431	0.050	PercentGrade (%)	-0.374	0.119
Carposted6065	6.040	0.995	Carposted6070	4.681	1.684
Carposted70	8.830	1.202	Super (%)	0.458	0.134
AdvisoryPresent	-2.698	0.648	RsWidth (ft)	0.276	0.174
LW (ft)	1.573	0.600	CurveRight	1.657	0.452
InverseSuper (%)	-8.228	1.927	TSpeedPC (mph)	0.123	0.070
N	1509		**N**	95	
R^2_{Adj}	0.556		**R^2_{Adj}**	0.909	
Root MSE	5.424		**Root MSE**	2.630	

Table 32 – Comparison of OLS and 3SLS models for Passenger Cars at Point 2

Table 33 displays the results for both the OLS model and 3SLS model for trucks at Point 1. The tables exhibit a comparison between the parameter coefficients and standard errors for all independent variables, as well as the goodness-of-fit estimates. As shown, the parameter estimates for independent variables that were present in both models are similar. The standard errors, however, are higher for the 3SLS model than the OLS model. This suggests that OLS linear regression underestimates the standard error of independent variables included in the model when endogenous predictor variables are not considered.

OLS Regression			**3SLS Regression**		
Variable	**Coef**	**SE**	**Variable**	**Coef**	**SE**
(Constant)	17.861	12.666	Constant	-10.298	19.682
InverseRadius (ft)	-6564.193	1201.205	InverseRadius (ft)	-4979.734	1969.353
PercentGrade (%)	-1.527	0.061	PercentGrade (%)	-1.311	0.158
Truckposted50	3.537	1.894	TruckPosted55	3.088	1.626
TruckPosted55	5.619	1.953	TruckPosted6070	12.433	1.444
TruckPosted6065	13.343	1.795	CurveRight	-4.334	0.593
TruckPosted70	18.055	1.980	LW (ft)	3.522	0.900
AdvisoryPresent	-1.968	0.970	Speed300 (mph)	0.254	0.218
LW (ft)	2.337	0.957	**N**	95	
N	1042		**R^2_{Adj}**	0.909	
R^2_{Adj}	0.541		**Root MSE**	2.630	
Root MSE	7.179				

Table 33 – Comparison of OLS and 3SLS models for Trucks at Point 1

Table 34 displays the results for both the OLS model and 3SLS model for trucks at Point 2. The table exhibits a comparison between the parameter coefficients and standard errors for all independent variables, as well as the goodness-of-fit estimates. As shown, the parameter estimates for independent variables that were present in both models are similar. The standard errors, however, are higher for the 3SLS model than the OLS model. This indicates that, when not accounting for potential endogeneity among truck and passenger car speeds, standard errors for single OLS linear regression models may be underestimated.

OLS Regression			**3SLS Regression**		
Variable	**Coef**	**SE**	**Variable**	**Coef**	**SE**
(Constant)	21.609	12.350	Constant	-12.765	20.249
InverseRadius (ft)	-7419.752	1179.606	InverseRadius (ft)	-5077.708	2487.855
PercentGrade (%)	-1.586	0.059	PercentGrade (%)	-1.311	0.184
TruckPosted5055	2.369	1.766	TruckPosted55	2.521	1.609
TruckPosted6065	11.400	1.761	TruckPosted6070	12.267	1.567
TruckPosted70	17.177	1.943	CurveRight	-4.394	0.608
AdvisoryPresent	-3.002	0.895	LW (ft)	3.507	0.894
LW (ft)	2.209	0.929	SpeedPC (mph)	0.295	0.250
N	1042		**N**	95	
$\mathbf{R^2_{Adj}}$	0.572		$\mathbf{R^2_{Adj}}$	0.912	
Root MSE	7.057		**Root MSE**	2.687	

Table 34– Comparison of OLS and 3SLS models for Trucks at Point 2

The independent variable InverseRadius was statistically significant in the OLS and 3SLS models for passenger cars and trucks at both Point 1 and Point 2. Figure 26 in Appendix B shows the expected passenger car speeds at different values of the radius of horizontal curve when all other variables are held constant at their mean values for the OLS model and 3SLS model. As shown, the results in predicted mean speeds and the shape of the trend line are similar for both models at Point 1 and Point 2. The differences between all of the speed profiles are minimal at both small and large values of horizontal curve radius. Figure 27 in Appendix B displays the predicted mean truck speeds at different values of the radius of horizontal curve when all other variables are held constant at their mean values for the OLS and 3SLS models. As shown, the results in both predicted mean speeds are similar for both models at Point 1 and Point 2. The 3SLS model trend line shape shows that horizontal curve radius has a slightly less effect on mean truck speed than on passenger car speed. The predicted speeds for the 3SLS models are greater at lower values of horizontal curve radius, but shift to being smaller at higher values of horizontal curve radius.

The independent variable PercentGrade was statistically significant in the OLS and 3SLS models for passenger cars and trucks at both Point 1 and Point 2. Figure 28 in Appendix B displays the predicted mean passenger car speeds at different values of the percent grade on the approach tangent when all other variables are held constant at their mean values for the OLS model and 3SLS model. As shown, the results in the predicted mean speeds and the shape of the trend line are similar for both models at Point 1 and Point 2. The differences between all of the speed profiles are minimal at both small and large values of percent grade. Figure 29 in Appendix B displays the predicted mean truck speeds at different values of the percent grade when all other variables are held constant at their mean values for the OLS and 3SLS models. As shown, the results in both predicted mean speeds are similar for both models at Point 1 and Point 2. The 3SLS model trend line shape shows that percent grade has a slightly less effect on mean truck speed. The predicted speeds for the 3SLS models are lower at very negative percent grades but shift to being greater at very positive percent grades.

An independent variable representing superelevation (InverseSuper or Super) was statistically significant in OLS linear regression and 3SLS models for passenger cars at both Point 1 and Point 2. Figure 30 in Appendix B displays the expected passenger car speeds at different values of superelevation on the approach tangent when all other variables are held constant at their mean values for the OLS and 3SLS models. As shown, the 3SLS model produced a linear relationship between superelevation and mean passenger car speed, whereas the OLS linear regression model had an inverse relationship. This profile plot shows that superelevation has a larger effect on mean passenger car speed for the 3SLS model, with the predicted speed being approximately equal at small values of superelevation but slightly higher at larger values of superelevation.

The independent variable LW was statistically significant in OLS linear regression and 3SLS models for trucks at both Point 1 and Point 2. Figure 31 in Appendix B shows the expected passenger car speeds at different values of lane width when all other variables are held constant at their mean values for the OLS model and 3SLS model. As shown, lane width had a much larger effect on mean truck speed for the 3SLS model than the OLS model. The effect of this variable changed the most out of all continuous variables between the 3SLS and OLS models.

The OLS linear regression models in the above comparison tables were developed from the disaggregate dataset and the 3SLS models were developed from the aggregate dataset. Therefore, there were 1509 observations for passenger cars and 1042 for trucks in the OLS models and only 95 observations for both passenger cars and trucks in the 3SLS models. The sample size disparity is the most likely the reason that there are predictor variables that are statistically significant or absent in the OLS models, but not in the 3SLS models. This is also the reason that the goodness-of-fit criterion (R^2_{Adj}) for the 3SLS models is much higher when compared to the OLS linear regression models. Table 35 displays the R^2_{Adj} values from the aggregate OLS models and the 3SLS models. As shown, the R^2_{Adj} values are higher and the root mean square error (MSE) values are lower for all 3SLS models than the equivalent OLS model. This demonstrates that the addition of the endogenous variable to the models improve the goodness-of-fit criterion. Thus, there is variability in the dependent variable that is being explained by these endogenous variables. It was also shown above that the parameter estimates between the developed

OLS models and 3SLS models were very similar. Therefore, it can be concluded that the 3SLS approach is a superior modeling technique for the data contained in this thesis based on the criteria of goodness-of-fit and parsimony.

Model	**OLS**		**3SLS**	
	R^2_{Adj}	**Root MSE**	**R^2_{Adj}**	**Root MSE**
Car - Point 1	0.878	5.49	0.888	1.915
Car - Point 2	0.882	2.085	0.896	2.003
Truck - Point 1	0.901	2.74	0.909	2.63
Truck - Point 2	0.905	2.806	0.912	2.687

Table 35 – OLS and 3SLS Goodness-of-Fit Comparisons for Aggregate Data

Chapter 8. CONCLUSIONS

This chapter summarizes the findings of this thesis in a clear and concise manner. All of the models that were developed offered parameter estimates that were similar to the expected results. All signs and magnitudes were logical and consistent with previous research when applicable.

Passenger Car Speeds

- Increasing horizontal curve radius and the horizontal curve superelevation rate increase the mean passenger car speed at Point 1 and Point 2.
- Increasing the grade of the approach decreases the mean passenger car speed at Point 1.
- Increasing lane width increases the mean passenger car speed at Point 2.
- Increasing the grade of the approach tangent and the presence of an advisory speed sign decrease the mean passenger car speed at Point 2.
- Increasing the posted speed limit increases mean passenger car speed at Point 1 and Point 2. This occurs proportionally as the posted speed limit (or intervals thereof) increases above the baseline posted speed limit.
- Horizontal curve radius had the largest influence on mean passenger car speeds at both Point 1 and Point 2. This influence is more severe on relatively sharper curves than flatter curves.
- The influence of horizontal curve superelevation rate is more severe on relatively smaller values of superelevation than larger values.

Truck Speeds

- Increasing lane width and horizontal curve radius increase the mean truck speed at Point 1 and Point 2.
- Increasing the grade of the approach tangent and the presence of an advisory speed sign decrease the mean truck speed at Point 1 and Point 2.
- Increasing the posted speed limit increases mean truck speed at Point 1 and Point 2. This occurs proportionally as the posted speed limit (or intervals thereof) increases above the baseline posted speed limit.
- Horizontal curve radius had a very large influence on mean truck speed for Point 1 and Point 2. This influence is more severe on relatively sharper curves than flatter curves.
- The approach tangent grade had a very large influence on mean truck speed for Point 1 and Point 2. This was prevalent for both negative grades (downgrades) and positive grades (upgrades).
- The presence of an advisory speed sign had a larger influence on mean truck speed at Point 2 than Point 1.

Overall Speed

- The mean truck speed was less than the mean passenger car at Point 1 and Point 2 for all independent variable values present in this study.
- The largest difference between mean truck speed and mean passenger car speed occurred on extremely positive values of percent grade (+6%).

- The difference between mean truck speed and mean passenger car speed was approximately the same for all values horizontal curve radius.

3SLS Model

- The 3SLS approach increased the standard error for independent variables when compared to the respective OLS models.
- Endogeneity existed between mean passenger car speeds and mean truck speeds on multilane highways.
- The 3SLS approach was a superior modeling technique based on the goodness-of-fit criterion.

Chapter 9. Recommendations

There are several recommendations that can be made for future work on this topic.

- The data collected only pertained to sites containing a steep grade and sharp horizontal curve. The volume of field data presented in this thesis should be collected at sites without these two features as necessary criteria. This would give a better understanding of the influence of geometric features on mean truck speeds without this interaction.
- The data collected in this thesis were for free-flow speeds under normal conditions. It is recommended that data be collected for truck speeds under non-ideal conditions, as this may factor into geometric design criteria and mean speed differences between passenger cars and trucks.
- Data should be collected for more independent variables than those considered in this thesis. Statistical tests for several truck models concluded that the models contained missing variables. Containing variables such as the length of departure tangent, the roadside hazard rating (RHR), interchange density, or clear zone widths could yield equations that more closely resemble those produced in existing research.
- The data collected in this thesis did not contain travel lane information (right-lane or left-lane) for passenger cars or trucks. This information should be collected and modeled for any possible interactions or endogenous relationships more consistent with previous research (Himes and Donnell 2010).

- A 3SLS modeling approach should be further explored to account for endogenous relationships between passenger car and truck speeds. This modeling technique should also be tested on larger datasets.
- Other modeling techniques should be considered for the data presented in this thesis. These modeling techniques (e.g. Newey-West estimator, WLS regression, HCSE) should attempt to fully correct the heteroskedasticity prevalent in the mean truck speed models.
- Future research should consider the relationship between geometric features and passenger car and truck speed variance. In the present study, data were collected at 19 sites thus the opportunity to estimate statistical models of speed variance was limited. It is recommended that speed data on multi-lane highways with speed grades and sharp horizontal curves be collected to compute speed variance that could be included in future statistical models.

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APPENDIX A: Descriptive Statistics

Location	**CA-1**	**CA-2**	**CA-3**	**WA-1**	**WA-2**	**WA-3**	**WA-4**	**WA-5**	**WA-6**	**WA-7**	**MD-1**	**MD-2**	**MD-3**	**PA-1**	**PA-2**	**WV-1**	**WV-2**	**WV-3**	**WV-4**	**WV-5**	**TOTAL**
-1200			39																		**39**
-1100			65																		**65**
-1000			72																		**72**
-900			77										84				30				**191**
-800			77	52									96				72	72			**369**
-700	15		77	76									89	60			70	89	18		**494**
-600	18		75	80								59	85	53			70	95	95		**630**
-500	21	30	75	80	41		54	46	30		59	74	82		11	25	67	95	98		**888**
-400	22	64	76	76	46		68	57	61		70	77	82		98	68	71	94	97		**1127**
-300	22	73	71	77	46	58	72	62	69	81	72	78	83		99	73	66	93	97		**1292**
-200	21	74	35	78	44	73	73	65	72	104	73	77	92	25	99	72	59	89	94		**1319**
-100	16	75		79	43	78	74	67	74	108	72	75	93	29	99	72	55	87	91		**1287**
0 (PC)		76		79	44	80	73	69	74	108	71	76	96	61	99	72	55	86	90		**1309**
100		76		74	43	79	71	67	73	107	71	75	101	68	99	73	52	85	91	61	**1366**
200		70		71	41	77	71	64	73	109	72	68	88	68	98	73	44	97	83	72	**1339**
300				70	38	77	72	62	72	114	71	62	74	59	98	73	36	97	19	71	**1165**
400				75	35	76	72	57	62	120	72	52	55	15	93	70	23	94		71	**1042**
500			34	78	40	65	71	49	59	120	71	46	49		89	69	13	78		69	**1000**
600			60	80	44	63	71	41	68	109	69	16			67	67		51		66	**872**
700			57	77	45	67	62	24	70		38				41	65		12		50	**608**
800				76	42	69	62	24	69		66				18	58	24			20	**528**
900		15		66	39	74	42	57	66		65	23				52	65			13	**577**
1000	19	71		35	35	75		68	64		61	26				45	69				**568**
1100	19				21	66		67	35		55	34				29	66				**392**
1200	21					50		66			49	26					66				**278**
1300	16							59			35	22					66				**198**
1400								35			19	11					63				**128**
1500																	59				**59**
1600																	54				**54**
1700																	55				**55**
1800																	48				**48**
1900																	43				**43**
2000																	33				**33**
2100																	25				**25**
2200																	23				**23**
2300																	12				**12**

Table 36 – Speed Data Counts for Every Site in 100 Foot Intervals Relative to the PC

Passenger Cars										Trucks									
Site	N	-300				PC				Site	N	-300				PC			
		Mean	Std Dev	Min	Max	Mean	Std Dev	Min	Max			Mean	Std Dev	Min	Max	Mean	Std Dev	Min	Max
WA1	82	63.78	5.20	53.3	74.6	62.58	5.43	52.3	74.8	WA1	63	56.51	3.62	47.5	63.9	63.00	3.49	46.8	60.9
WA2	47	69.75	4.07	58.7	77.8	69.41	4.39	58.5	78.0	WA2	51	60.73	4.61	47.7	69.0	60.44	4.32	48.1	68.9
WA3	80	69.84	4.76	55.0	80.5	70.32	4.64	55.1	83.0	WA3	45	58.48	6.48	42.4	72.0	59.00	5.98	43.1	72.0
WA4	76	68.03	3.81	57.4	75.2	67.81	3.96	55.7	74.9	WA4	38	59.02	4.31	45.9	66.0	58.83	4.15	45.3	66.1
WA5	72	58.44	5.86	38.6	73.8	58.22	5.65	38.1	72.5	WA5	76	46.19	11.53	18.7	62.6	45.20	11.38	18.3	62.0
WA6	74	68.75	3.59	61.2	77.0	68.91	3.63	60.8	77.0	WA6	55	60.96	4.99	31.9	69.0	61.65	2.83	54.7	69.0
WA7	117	53.49	6.13	35.6	69.6	51.04	5.85	35.0	69.2	WA7	24	40.51	10.65	18.3	59.5	39.55	10.06	17.6	56.1
CA1	31	65.14	6.74	52.0	80.6	64.37	6.67	52.0	79.1	CA1	67	52.98	3.98	43.9	66.0	52.10	3.79	43.9	65.1
CA2	76	52.44	5.46	31.1	65.9	52.42	5.44	31.5	67.0	CA2	43	42.37	5.49	34.2	55.0	42.25	5.37	34.1	54.0
CA3	79	53.42	3.91	45.5	63.5	51.34	3.54	41.4	61.0	CA3	38	41.31	7.30	29.1	55.1	39.67	6.10	29.3	51.7
WV1	73	66.77	5.65	53.8	80.6	66.40	6.23	42.0	79.0	WV1	52	62.34	5.03	49.0	70.8	62.45	4.96	49.0	71.8
WV2	76	66.52	7.64	40.1	80.7	66.35	7.02	43.2	80.3	WV2	44	55.88	7.33	43.9	78.3	55.65	7.31	44.2	77.9
WV3	98	67.39	5.49	52.0	81.6	67.06	5.50	52.2	81.1	WV3	52	63.62	4.66	51.9	73.3	63.16	4.77	52.1	73.4
WV4	98	63.97	5.41	47.3	81.2	62.67	5.42	46.0	77.8	WV4	72	58.25	4.09	49.3	66.6	57.25	3.85	49.7	64.8
WV5	73	66.14	5.61	48.5	77.7	67.51	4.59	52.7	76.2	WV5	51	64.26	5.08	50.8	80.0	65.37	4.26	55.5	76.1
MD1	73	65.66	4.87	54.6	75.4	65.60	4.76	54.0	75.4	MD1	49	63.06	3.54	51.0	69.1	62.76	3.48	51.6	69.2
MD2	80	63.93	7.43	33.5	89.4	63.36	7.52	32.6	89.1	MD2	73	42.80	13.80	20.2	71.0	42.15	13.74	20.5	70.7
MD3	104	68.66	5.10	56.9	86.8	67.86	5.23	55.2	87.2	MD3	77	64.60	5.43	45.4	78.0	64.32	5.36	46.0	78.0
PA2	100	67.13	4.44	56.0	77.2	66.71	4.60	56.0	75.9	PA2	72	65.52	4.18	54.3	76.9	65.06	4.60	52.6	76.3
Total	**1509**	**63.91**	**7.77**	**31.1**	**89.4**	**63.35**	**8.14**	**31.5**	**89.1**	**Total**	**1042**	**56.33**	**10.59**	**18.3**	**80.0**	**55.89**	**10.72**	**17.6**	**78.0**

Table 37 – Descriptive Statistics for Speed (mph)

Variable	Description	Mean	Std Dev	Min	Max
InverseRadius	Inverse of the radius of horizontal curve (ft)	0.000816	0.000456	0.000357	0.001862
LcFt	Length of the horizontal curve (ft)	1533.98	620.85	264	2640
PercentGrade	Percent of the approach tangent (%)	-3.03	4.04	-6.3	6.0
LgFt	Length of the approach tangent grade (ft)	6405.47	4990.38	1109	21120
InverseSuper	Inverse of the superelevation on the horizontal Curve (%)	0.17	0.12	0.83	0.5
LW	Average lane width at the PC (ft)	11.82	0.36	11	13
LsWidth	Shoulder width on the left side of the roadway (ft)	5.50	3.38	0	15
RsWidth	Shoulder width on the right side of the roadway (ft)	9.18	1.85	2	10
MedianWidth	Median width, measured from the inside edge of the traveled way in opposing directions of travel (ft)	63.16	223.36	0	1000
CurveRight	Indicator for the presence of a horizontal curve to the right	0.421	0.498	0	1
AdvisoryPresent	Indicator for the presence of a reduced speed advisory sign	0.421	0.498	0	1
SpiralIndicator	Indicator for the presence of a spiral-designed horizontal curve	0.421	0.498	0	1
DividedIndicator	Indicator for the presence of a divided highway	0.95	0.225	0	1
CarPosted60	Indicator for the presence of a posted speed limit of 60 mph for passenger cars	0.21053	0.41131	0	1
CarPosted65	Indicator for the presence of a posted speed limit of 65 mph for passenger cars	0.26316	0.44426	0	1
CarPosted70	Indicator for the presence of a posted speed limit of 70 mph for passenger cars	0.42105	0.49812	0	1
TruckPosted50	Indicator for the presence of a posted speed limit of 50 mph for trucks	0.10526	0.30962	0	1
TruckPosted55	Indicator for the presence of a posted speed limit of 55 mph for trucks	0.05263	0.22528	0	1
TruckPosted60	Indicator for the presence of a posted speed limit of 60 mph for trucks	0.47368	0.50375	0	1
TruckPosted65	Indicator for the presence of a posted speed limit of 65 mph for trucks	0.21053	0.41131	0	1
TruckPosted70	Indicator for the presence of a posted speed limit of 70 mph for trucks	0.10526	0.30962	0	1

Table 38 – Descriptive Statistics for Independent Variables Considered in the Model Building Procedure

	CurveRight	**CarPosted60**	**CarPosted65**	**CarPosted70**	**TruckPosted50**	**TruckPosted55**	**TruckPosted60**	**TruckPosted65**	**TruckPosted70**	**AdvisoryPresent**	**PercentGrade**
CurveRight	1										
CarPosted60	-0.1789	1									
CarPosted65	-0.0255	-0.3086	1								
CarPosted70	0.1364	-0.4404	-0.5096	1							
TruckPosted50	-0.2925	-0.1771	-0.205	0.0548	1						
TruckPosted55	-0.201	-0.1217	0.3944	-0.201	-0.0808	1					
TruckPosted60	0.2584	0.5443	-0.5669	0.2584	-0.3254	-0.2236	1				
TruckPosted65	0.0826	-0.2667	0.8641	-0.4404	-0.1771	-0.1217	-0.4899	1			
TruckPosted70	-0.2925	-0.1771	-0.205	0.4022	-0.1176	-0.0808	-0.3254	-0.1771	1		
AdvisoryPresent	-0.0795	0.0826	-0.5096	0.1364	0.4022	-0.201	-0.1685	-0.4404	0.4022	1	
PercentGrade	-0.0922	0.446	0.127	-0.3103	-0.2542	-0.0039	0.1943	0.1394	-0.1085	-0.1806	1
LgFt	0.2258	-0.1905	-0.2304	0.582	-0.1458	0.0973	0.3546	-0.3022	0.0757	-0.1542	-0.0141
InverseRad	-0.0491	0.1871	-0.3688	-0.2902	0.2396	-0.1647	-0.0824	-0.3081	0.0266	0.7181	0.0088
LcFt	-0.0313	-0.1463	0.346	0.0327	0.0573	0.363	-0.2394	0.1749	-0.0457	-0.1868	0.0228
Super	-0.1025	0.1945	0.2328	-0.244	-0.1381	0.5024	0.0429	0.0717	-0.1305	-0.4503	0.3701
SpiralIndicator	-0.2955	0.3441	-0.2676	0.1364	0.0548	-0.201	0.0449	-0.1789	0.4022	0.5682	-0.0875
DividedIndicator	0.201	-0.4564	0.1409	0.201	0.0808	0.0556	-0.2485	0.1217	0.0808	0.201	-0.5318
MedianWidth	-0.2105	-0.1473	0.4255	-0.1971	-0.0669	-0.0672	-0.2706	0.4965	-0.0545	-0.1971	-0.0583
LW	0.171	-0.2914	0.2975	-0.1823	0.0105	0.1174	-0.5756	0.2571	0.1708	0.174	-0.4023
LsWidth	-0.2067	0.1155	0.1248	-0.0159	-0.1023	0.668	0	-0.2311	0.1023	0.2385	0.0552
RsWidth	-0.1733	0.0891	0.0705	0.2928	0.0592	-0.0237	0.2213	0.0891	0.1529	-0.348	0.1122

	LgFt	**InverseRad**	**LcFt**	**InverseSuper**	**SpiralIndicator**	**DividedIndicator**	**MedianWidth**	**LW**	**LsWidth**	**RsWidth**
LgFt	1									
InverseRad	-0.4144	1								
LcFt	0.2283	-0.4248	1							
InverseSuper	-0.0513	-0.3667	0.0999	1						
SpiralIndicator	-0.0689	0.1567	0.051	-0.3956	1					
DividedIndicator	0.0889	0.1069	0.2033	-0.7765	0.201	1				
MedianWidth	-0.1436	-0.1292	-0.0039	-0.1098	0.2844	0.0672	1			
LW	-0.1091	-0.0251	0.228	-0.0841	0.1227	0.2164	0.142	1		
LsWidth	0.1253	0.0823	0.2943	-0.172	0.3975	0.3867	-0.1129	-0.0738	1	
RsWidth	0.2829	-0.6847	0.2069	0.2583	0.0598	-0.1051	-0.1327	-0.3581	0.0558	1

Table 39 – Correlation Matrix of Independent Variable

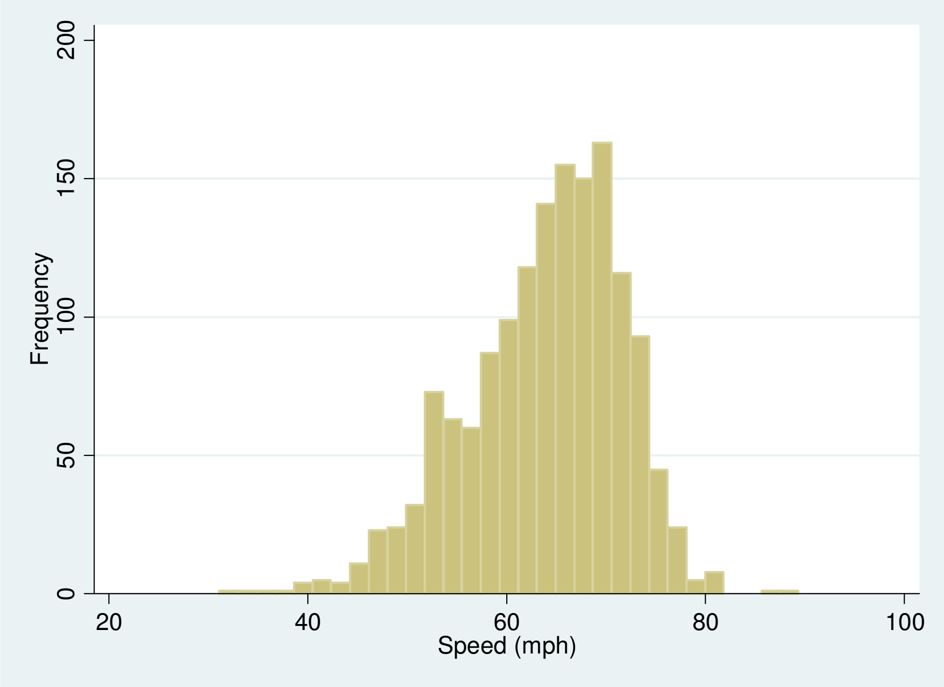

Figure 18 – Histogram of Passenger Car Speeds at Point 1

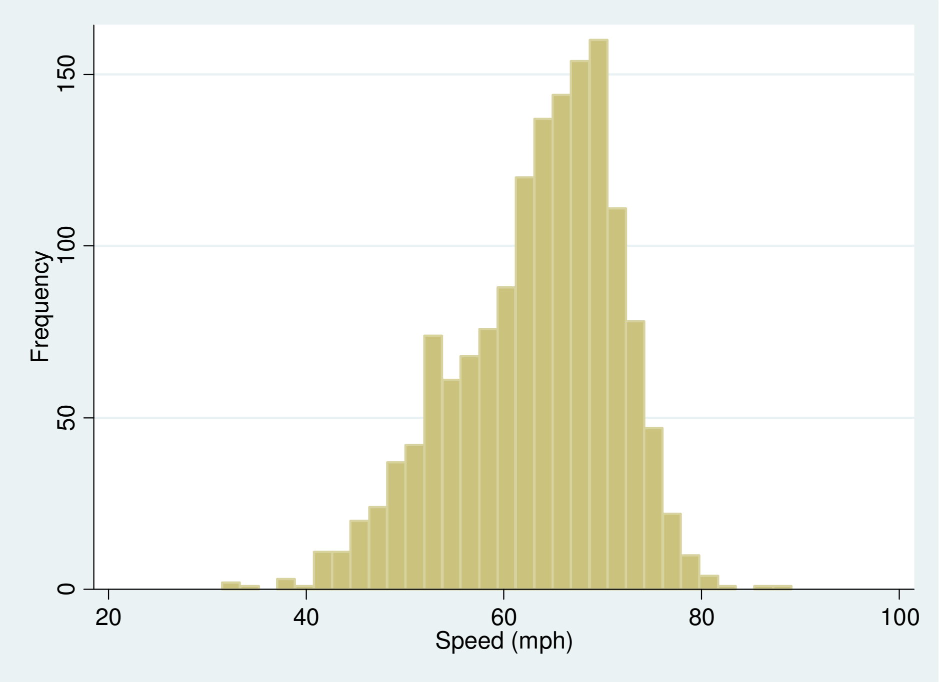

Figure 19 – Histogram of Passenger Car Speeds at Point 2

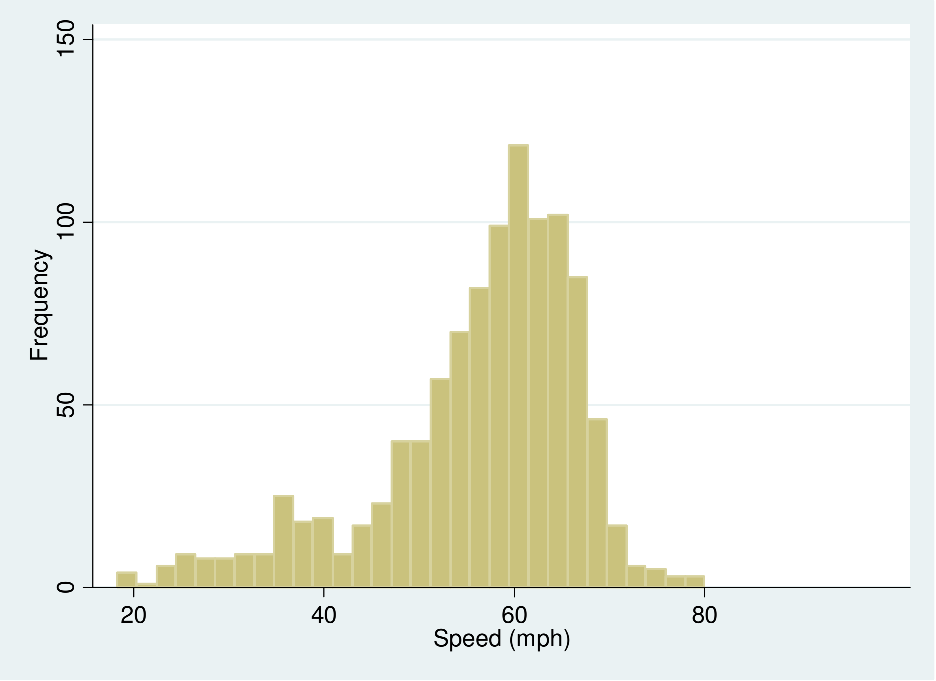

Figure 20 – Histogram of Truck Speeds at Point 1

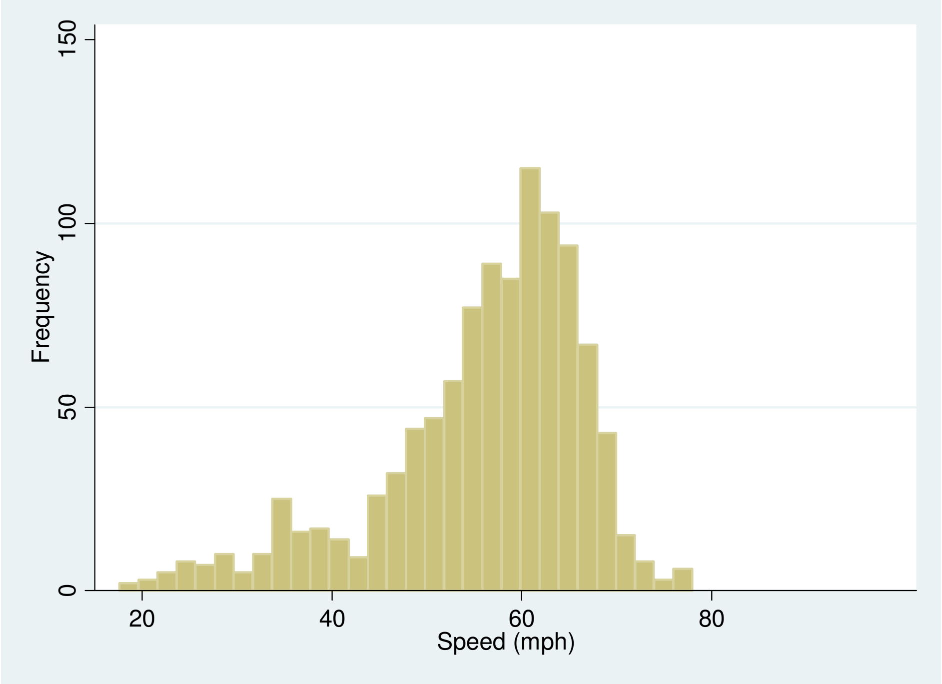

Figure 21 – Histogram of Truck Speeds at Point 2

APPENDIX B: Speed Profile Plots

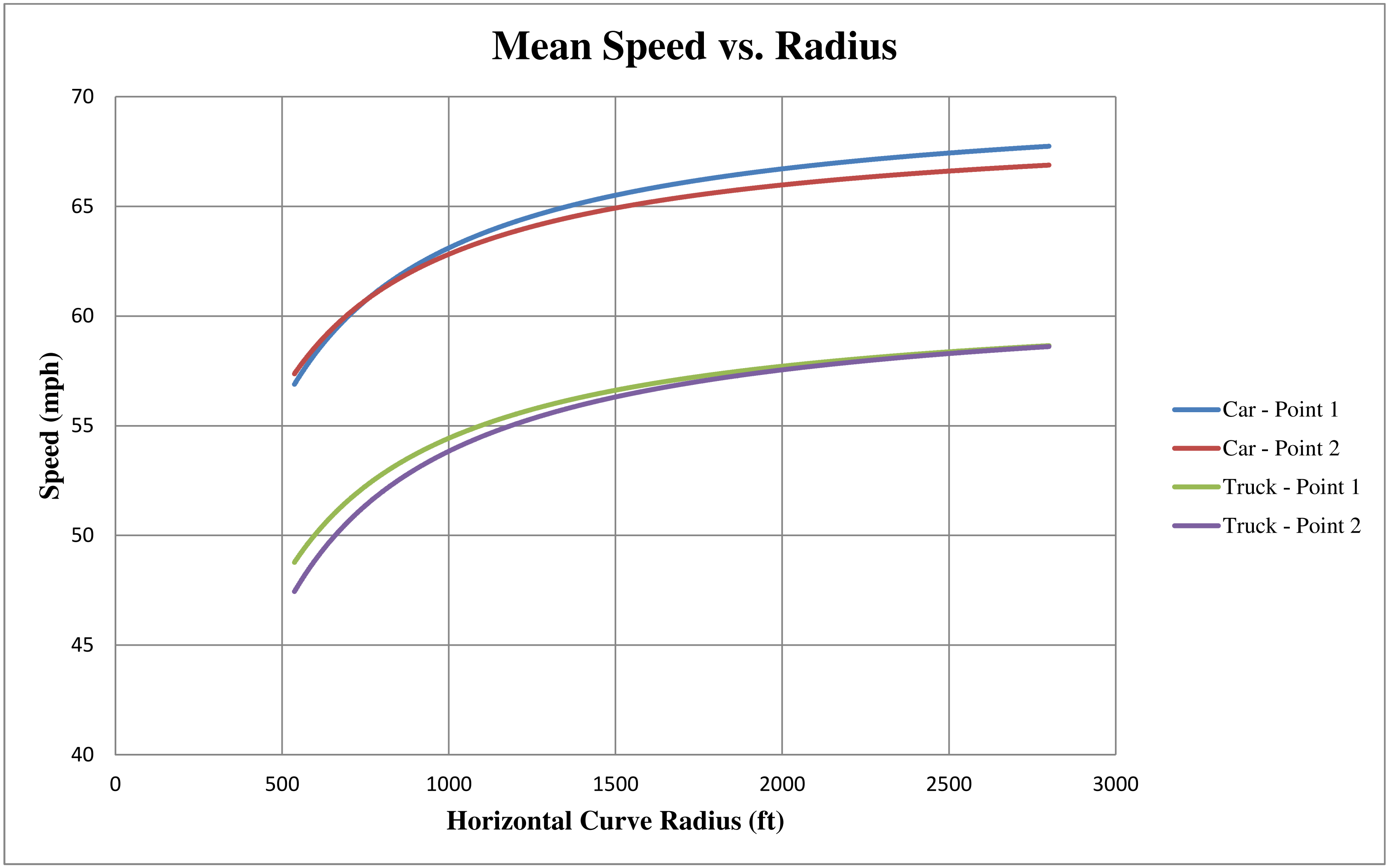

Figure 22 – Speed Profile Plot of Horizontal Curve Radius for OLS models

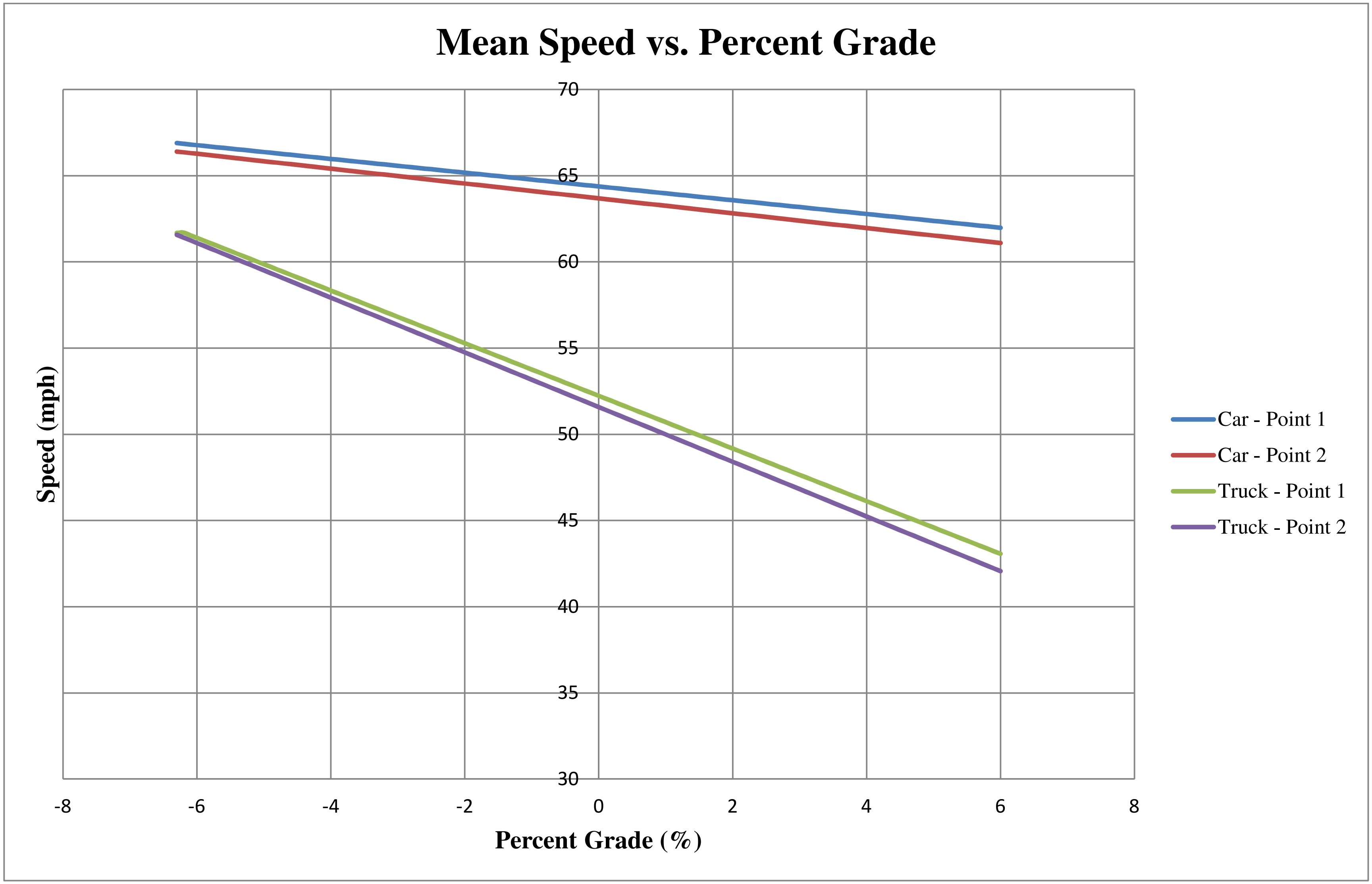

Figure 23 – Speed Profile Plot of Percent Grade for OLS models

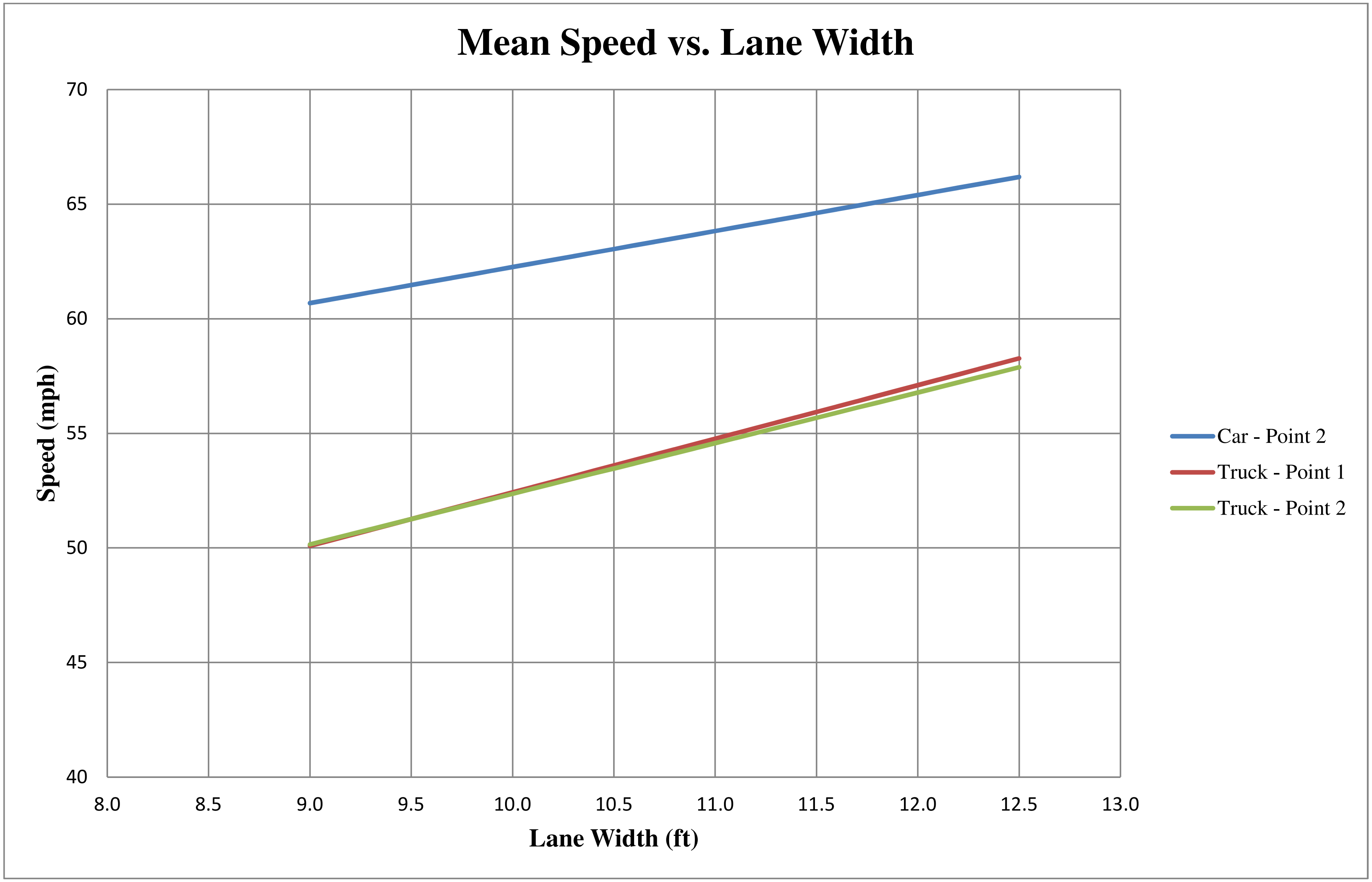

Figure 24 – Speed Profile Plot of Lane Width for OLS models

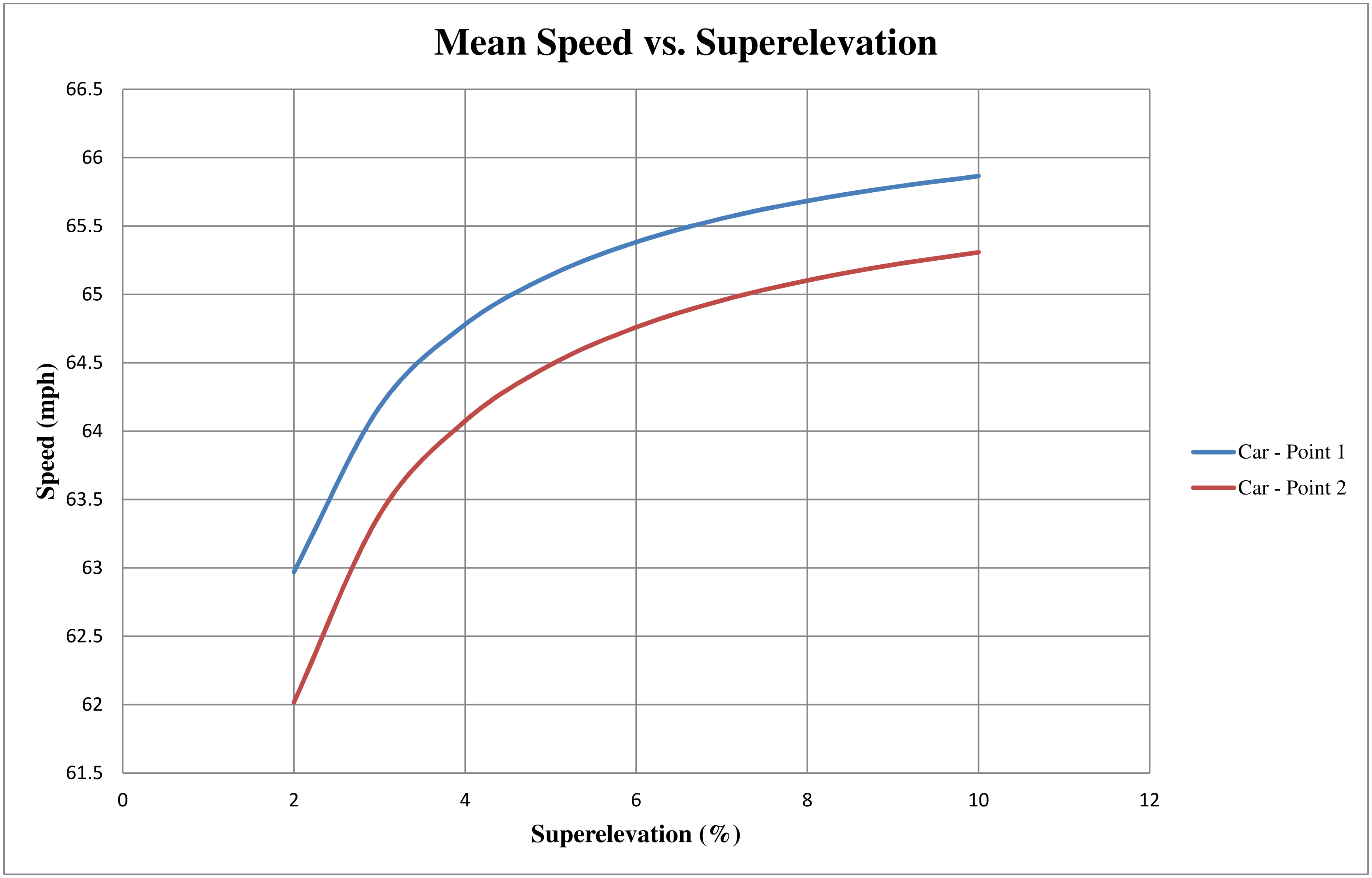

Figure 25 – Speed Profile Plot of Superelevation for OLS models

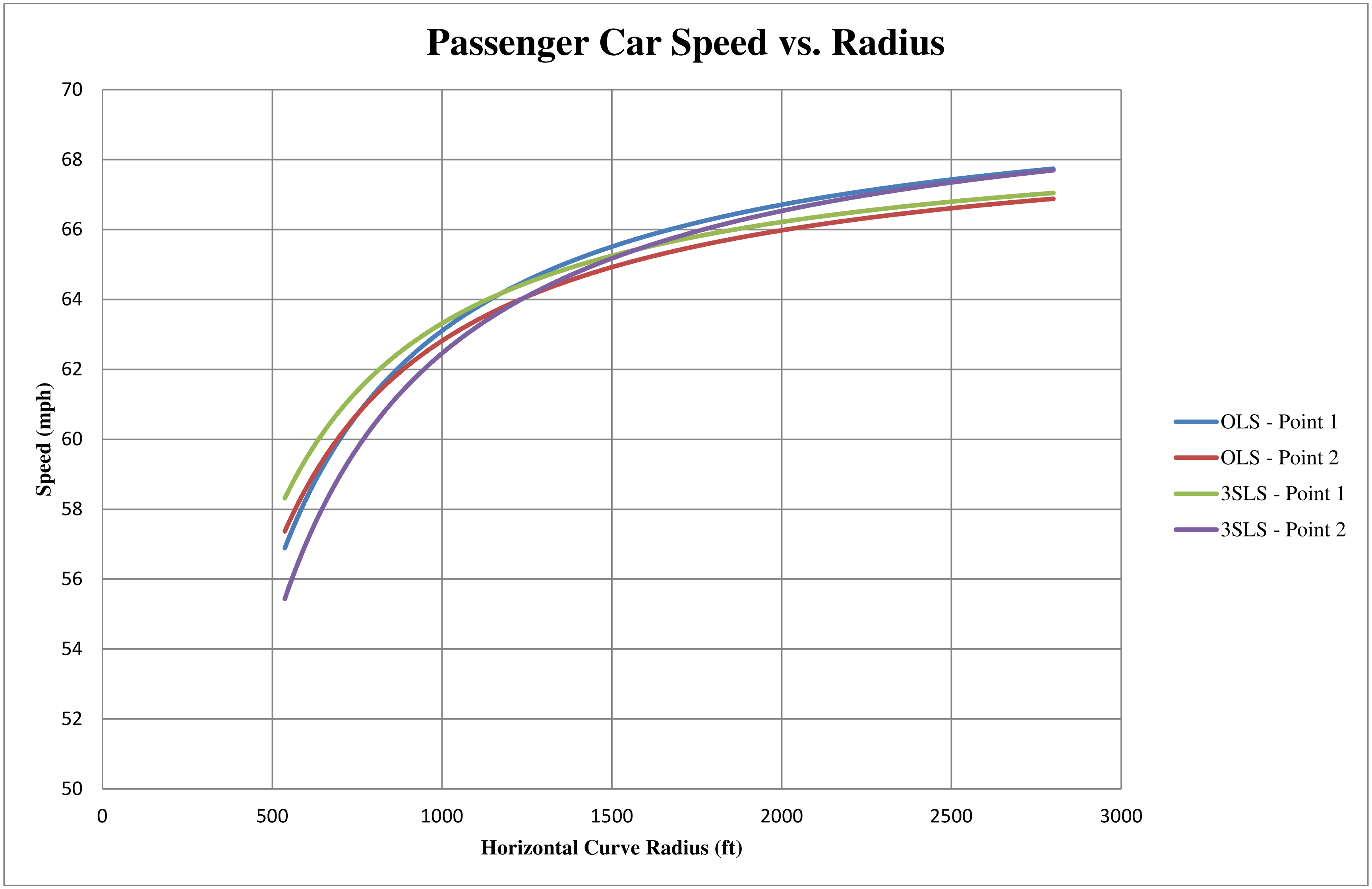

Figure 26 – Passenger Car Speed Profile Plot of Horizontal Curve Radius for OLS and 3SLS models

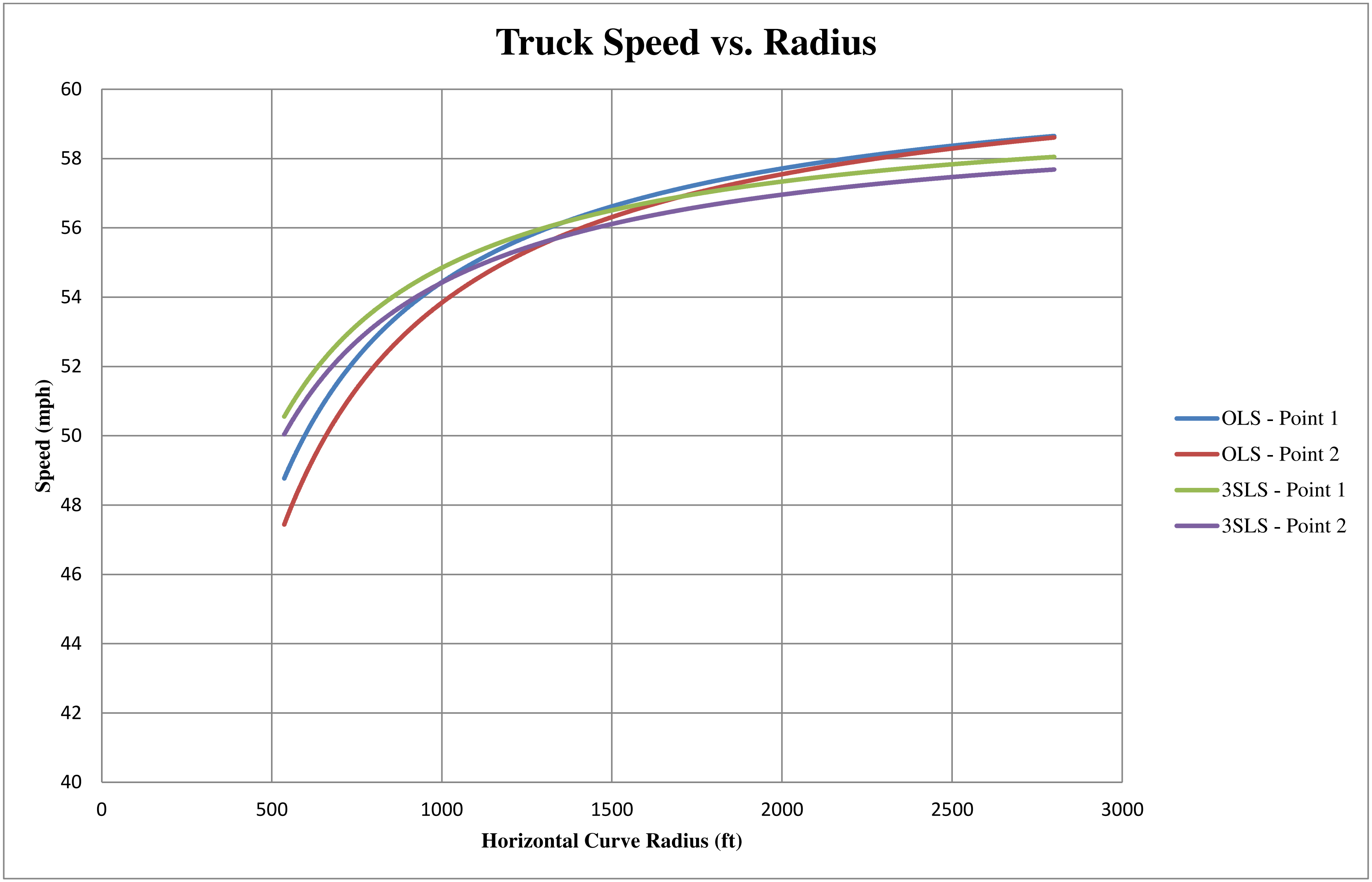

Figure 27 – Truck Speed Profile Plot of Horizontal Curve Radius for OLS and 3SLS models

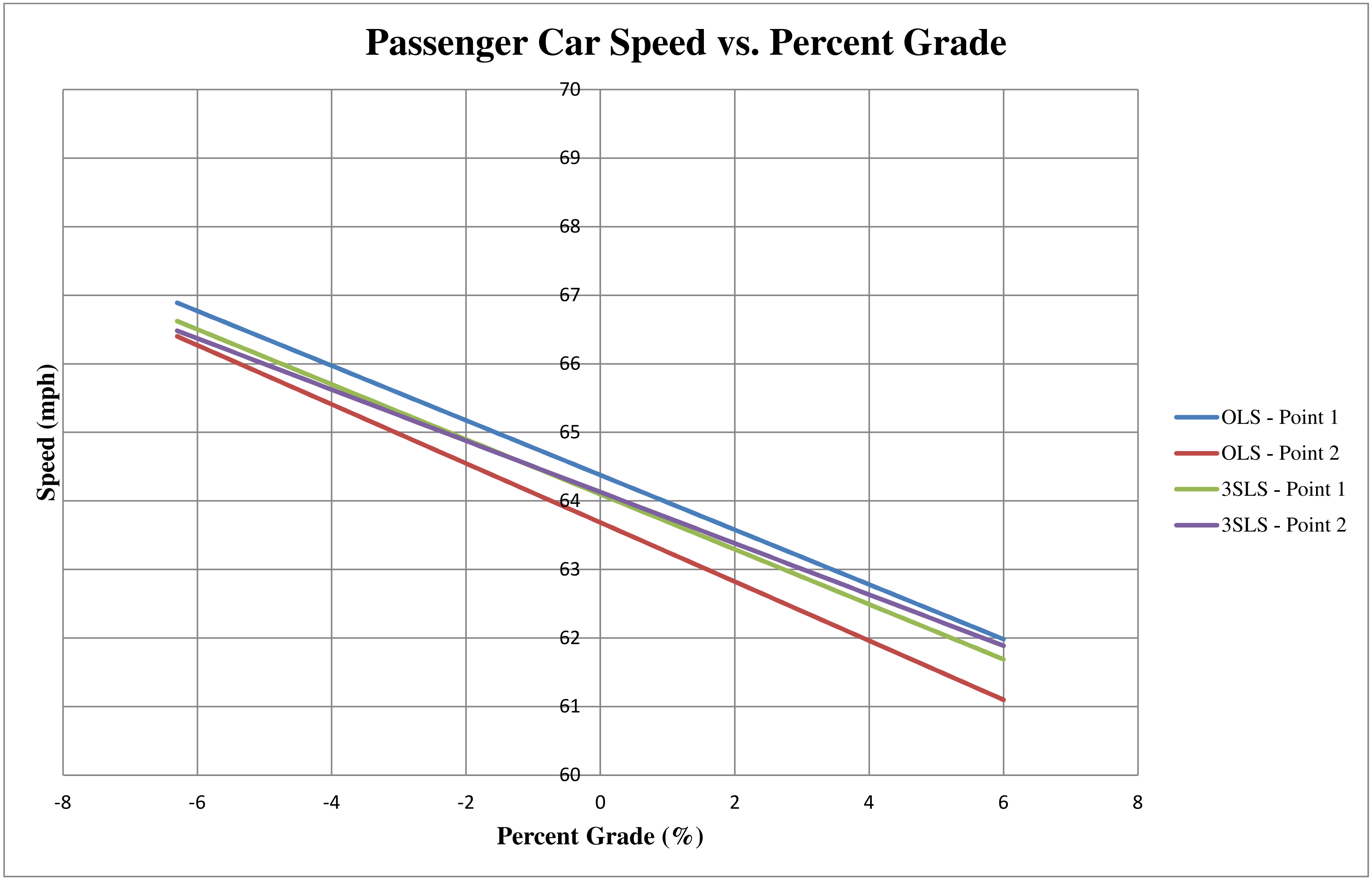

Figure 28 – Passenger Car Speed Profile Plot of Percent Grade for OLS and 3SLS models

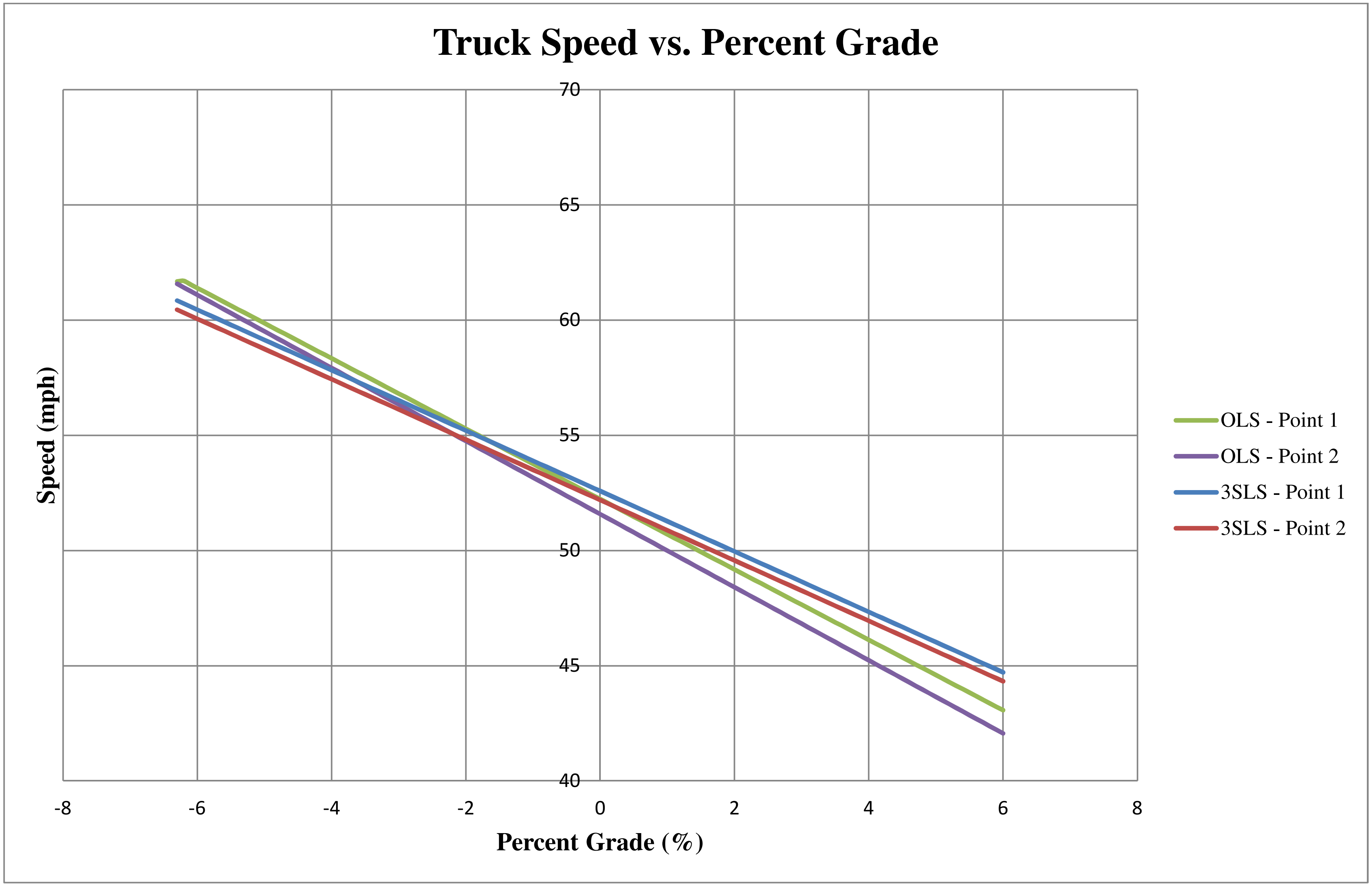

Figure 29 – Truck Speed Profile Plot of Percent Grade for OLS and 3SLS models

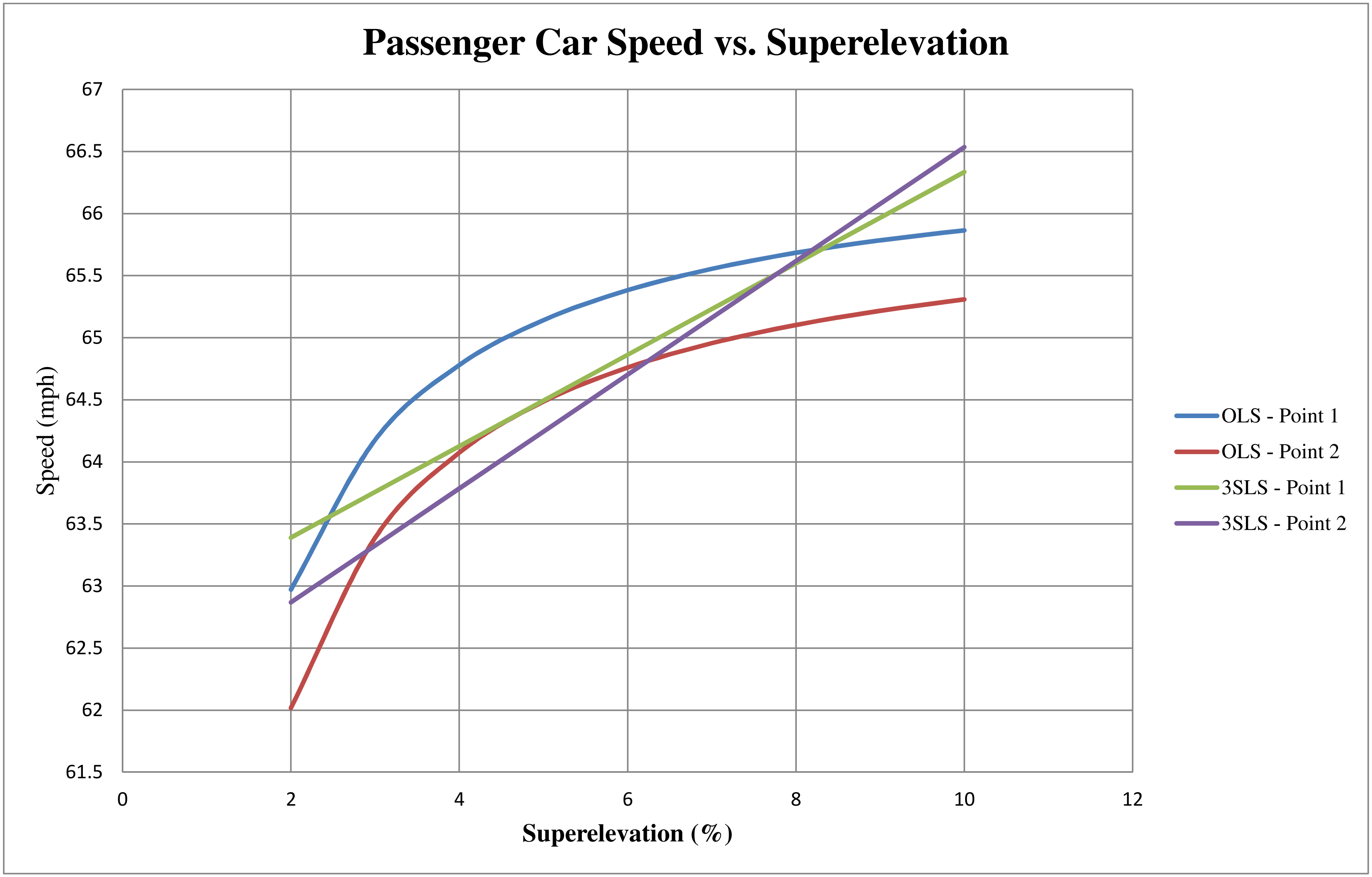

Figure 30 – Passenger Car Speed Profile Plot of Superelevation for OLS and 3SLS models

Figure 31 – Truck Profile Plot of Lane Width for OLS and 3SLS models

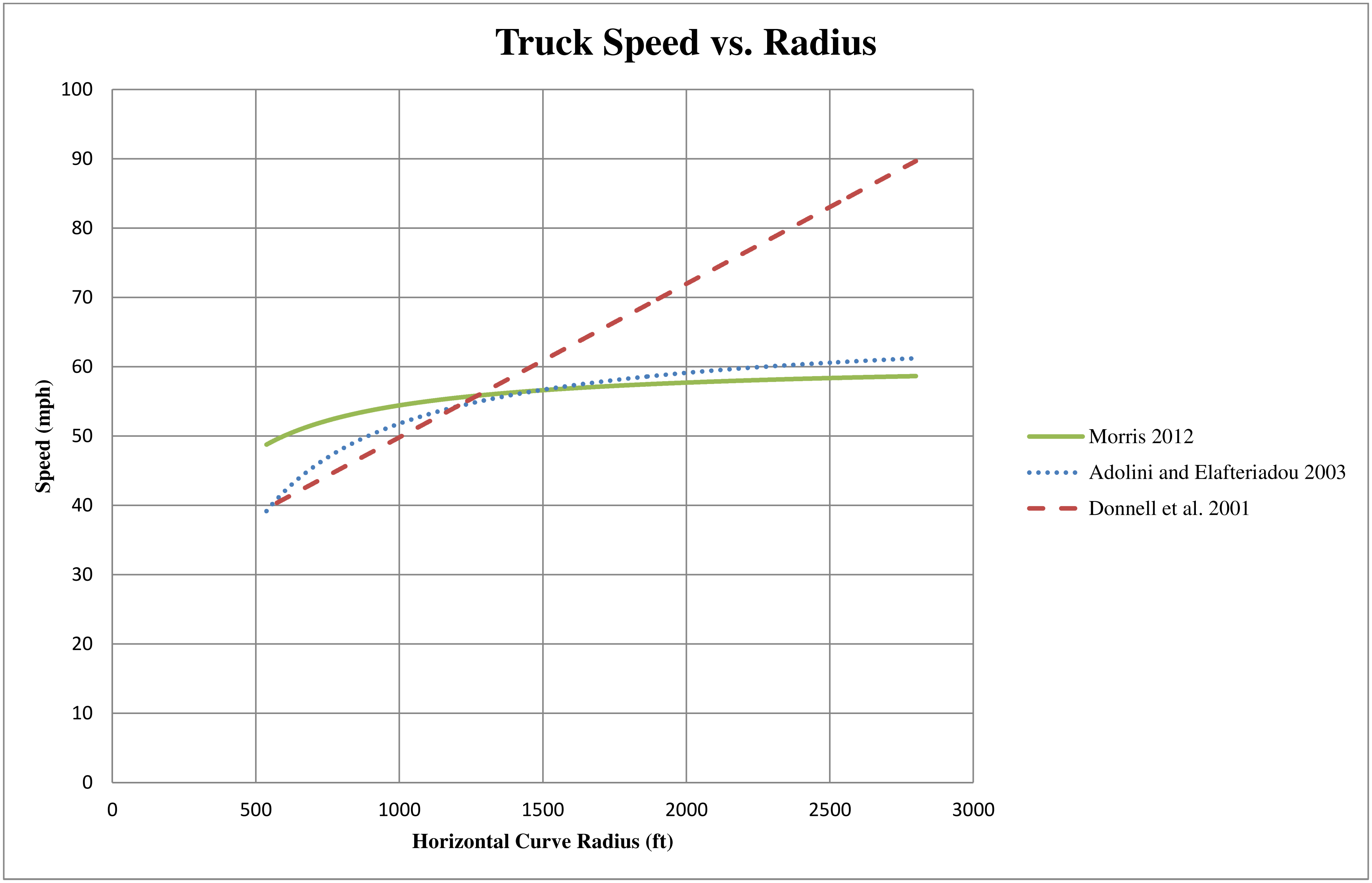

Figure 32 – Truck Profile Plot with Previous Research at Point 1

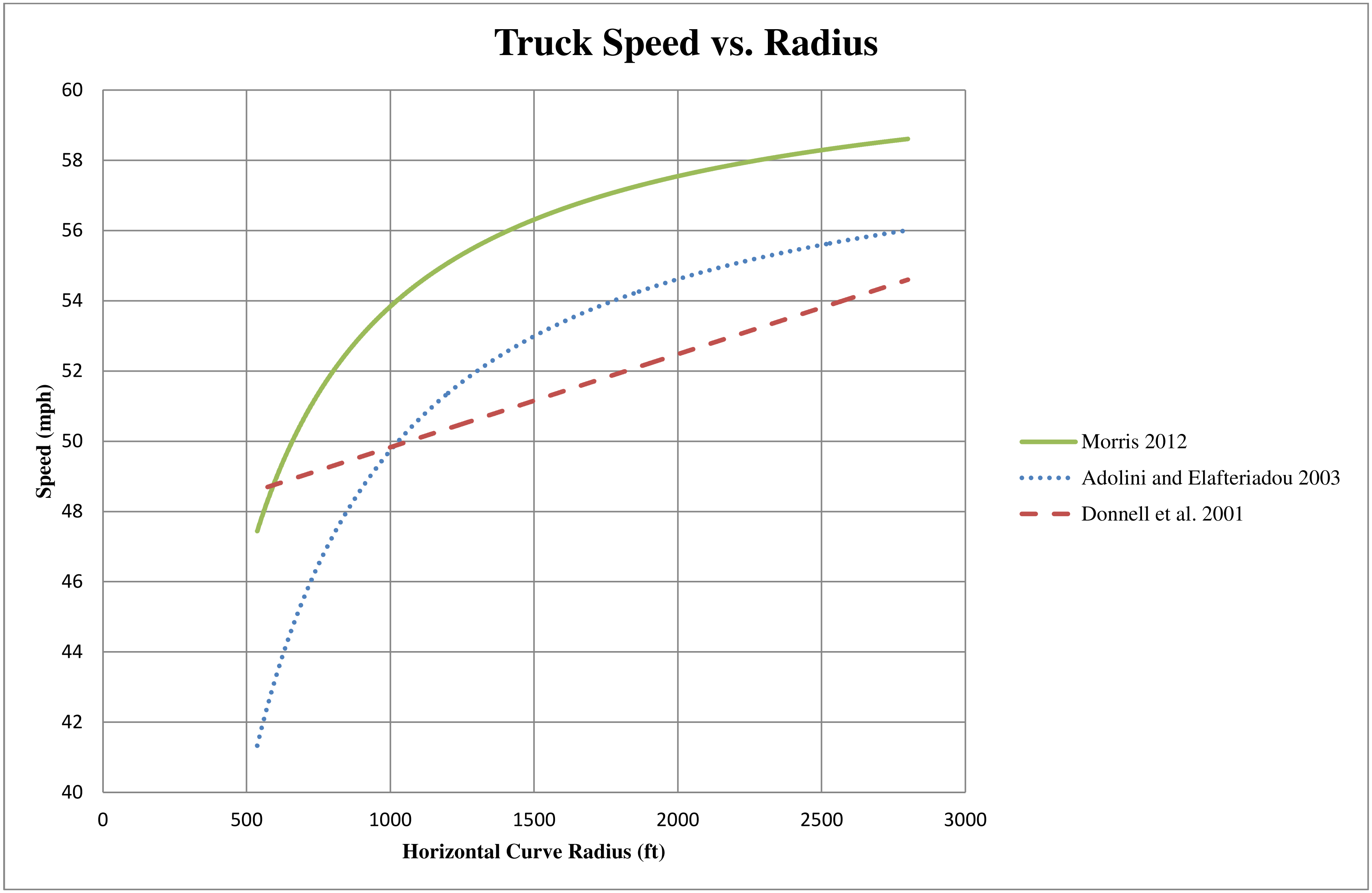

Figure 33 – Truck Profile Plot with Previous Research at Point 2