

SOME NEW INSIGHTS ON DESIGN CONSISTENCY EVALUATIONS FOR TWO-LANE HIGHWAYS

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ABSTRACT

There is a significant body of published literature related to operating speed prediction along horizontal curves of two-lane rural highways. Operating speed models for two-lane rural highway tangents as well as horizontal curves on low-speed urban streets also exist, but are less developed. These models, developed primarily with least squares regression techniques, generally use aggregate-level data to estimate geometric design effects on the mean or 85th-percentile operating speed, but do not explicitly consider measures of speed dispersion (e.g., standard deviation). Most existing models consider speeds of free-flow passenger vehicles; traffic flow effects are not quantified. Finally, published literature shows that researchers have not converged on a consistent modeling practice regarding the use of posted speed limit as an explanatory variable. Collectively, these issues may lead to design consistency assessments that are not truly reflective of the operating conditions present along a two-lane highway. These issues are explored in this paper using operating speed data collected at multiple points along eight two-lane highway segments. A simultaneous equations modeling approach is used to estimate a three-equation model of the posted speed limit (treated here as a continuous, endogenous variable), mean speed, and speed deviation. The predicted 85th-percentile speed is compared to the observed 85th percentile speed along a high-speed, two-lane rural highway. Predicted 85th-percentile operating speeds along the same high-speed highway using the IHSDM design consistency module are also compared to observed 85th percentile speeds as a basis for evaluating the simultaneous equation model approach. Finally, an alternative design consistency evaluation approach is proposed using inferred design speed.

INTRODUCTION

A significant body of literature exists to evaluate design consistency on two-lane rural highways. Much of the published research makes use of linear regression models to predict operating speeds along horizontal alignment features (i.e., horizontal curves and tangents). Predicted operating speeds on these features are compared to each other or to the designated design speed to evaluate design consistency. The 85th percentile of the free-flow speed distribution is commonly used to represent operating speed for design consistency evaluations. Such an approach does not account for the entire distribution of speeds observed at a location; valuable information regarding speed extremes is lost. For example, the same 85th percentile speed may be observed at two locations that have very different 95th or 99th percentile speeds.

Several other issues limit the potential utility of existing speed-based design consistency evaluation methods. First, most existing operating speed models do not include the posted speed limit in the model. Omitted variable bias may occur if the posted speed limit is not included in the model specification, which is potentially a more serious modeling issue than correlation between explanatory variables if posted speed is included. Second, most existing operating speed models consider only free-flow vehicles in the data sample. Such an approach does not account for changing highway flow rates; estimated models reflect only the desired speed of a driver unimpeded by other traffic and these do not demonstrate the range of speeds expected on a segment. Third, research has shown that 85th percentile operating speeds often exceed the designated design speed on a highway segment without necessarily a safety concern. A plausible explanation for this frequently observed relationship is that designers are encouraged to exceed minimum design criteria for a designated design speed. Comparisons of operating and inferred design speeds may be more meaningful. Finally, past operating speed prediction models generally focus on tangent-curve combinations that meet certain site selection criteria without comprehensive consideration of a combination of roadway and roadside design elements that constitute an entire alignment and surrounding roadway environment. The transferability of the resulting models is unknown because they do not account for the various dynamics associated with operating speeds at a particular point location, such as the effect of adjacent horizontal or vertical design elements, available sight distance, land use characteristics, and roadside features.

The purpose of this paper is to provide some new insights related to geometric design consistency on rural and urban two-lane highways, with particular focus on exploring the aforementioned speed-modeling issues. A simultaneous equations approach is used that explicitly considers the posted speed limit in the mean and speed deviation estimations, while also considering hourly traffic flow rates. As a means to demonstrate the utility of the proposed modeling approach, the results from the present study are compared to observed speeds and to results of existing design consistency evaluation methods. Finally, an alternative design consistency approach is proposed that uses the inferred design speed in an instrumented variable modeling framework. It is hypothesized that large differences between the inferred design speed and the 85th-percentile speed along an alignment may provide useful insights regarding geometric design consistency that is not currently detected using existing design consistency evaluation methods.

DESIGN CONSISTENCY AND SPEED PREDICTION LITERATURE

The design consistency concept was first proposed by Leisch and Leisch in 1976 (1) as an alternative to the design speed approach. The authors' proposed the following principles:

- For a given design speed, the potential average automobile speeds should not vary more than 15 km/hr (10 mph) along an alignment.
- When a reduction in design speed is necessary, it should normally be no more than 15 km/hr (10 mph).
- On mixed-use lanes, average truck speeds should generally be no more than 15 km/hr (10 mph) lower than average automobile speeds.

The 15 km/hr (10 mph) threshold was based on several facts. The first was the perception that under most circumstances, drivers can manage reasonably well with a 15 km/hr (10 mph) speed adjustment. Also, evidence shows that accident involvement increases with increasing variations from the average speed. Finally, there is a sharp increase in the number of accidents as the difference in mean speed of passenger cars and trucks increase. The speed profile was also introduced as a tool to estimate speed reductions for automobiles and trucks based upon the roadway alignment. It was noted that at locations where speed increases occur, appropriately higher sight distances and superelevation rates on horizontal curves should be provided. Additionally, Leisch and Leisch (1) noted that should a change in design speed become necessary, justification for the reduced design speed should be obvious and acceptable to the driver.

McLean (2) examined the relationship between horizontal curve design and operating speeds on 120 curve sites in Australia. Three criticisms of the design speed concept were noted. First, roadway designs that conform to design speed standards do not ensure a consistent alignment. Secondly, designs that conform to a specified design speed do not ensure compatibility between combinations of design elements. Finally, free-flow speeds and design speed are not necessarily equal. McLean (2) proposed that horizontal curves within a section of roadway should not differ in design speed standard by more than an absolute maximum of 10 km/hr (6 mph). For isolated curves at the end of long tangents, it was recommended that a speed reduction of more than 10 km/hr (6 mph) should not be introduced, and a reduction of more than 15 km/hr (10 mph) is unacceptable. When transitioning from a high speed to lower speed environment, the predicted operating speed on sequential horizontal curves should not differ by more than 10 km/hr (6 mph).

Lamm, et al. (3) also established a process for evaluating horizontal design consistency. The authors established a classification system for differentiating good design from poor design. These were as follows:

- Good Design
 - $\Delta DC \leq 5^\circ$
 - $\Delta V_{85} \leq 6 \text{ mph (10 km/hr)}$
- Fair Design
 - $5^\circ < \Delta DC \leq 10^\circ$

- 6 mph (10 km/hr) < $\Delta V_{85} \leq 12$ mph (20 km/hr)
- Poor Design
 - $\Delta DC > 10^\circ$
 - $\Delta V_{85} > 12$ mph (20 km/hr)

where: ΔDC = the change in the degree of curvature
 ΔV_{85} = the change in 85th percentile speed

The classifications were based upon mean accident rates for each group by degree of curve. The above classifications were used to examine a design based upon the speed reduction from a horizontal tangent to a horizontal curve. The classification system was also recommended for estimating the difference between the 85th percentile operating speed and the designated design speed. If the expected 85th percentile operating speed was not more than 6 mph (10 km/hr) greater than the designated design speed, the design was considered “good.”

Fitzpatrick, et al. (4) developed an operating speed prediction methodology for inclusion in the Interactive Highway Safety Design Model (IHSDM). Similar to previous methods, operating speeds were estimated for horizontal curves based on the radius of curve. Vertical curvature was also considered in the development of speed prediction models. Models were classified by the vertical grade, and the rate of vertical curvature was included within the models. The speed prediction equations are shown in Table 1.

Table 1. Speed-Prediction Equations from Fitzpatrick et al. (4)

Alignment Condition	Equation	No Obs.	R ²
Horizontal Curve on Grade: -9 % ≤ G < -4 %	$V_{85} = 102.10 - (3077.13/R)$	21	0.58
Horizontal Curve on Grade: -4 % ≤ G < 0 %	$V_{85} = 105.98 - (3709.90/R)$	25	0.76
Horizontal Curve on Grade: 0 % ≤ G < 4 %	$V_{85} = 104.82 - (3574.51/R)$	25	0.76
Horizontal Curve on Grade: 4 % ≤ G < 9 %	$V_{85} = 96.61 - (2752.19/R)$	23	0.53
Horizontal Curve Combined with Sag Vertical Curve	$V_{85} = 105.32 - (3438.19/R)$	25	0.92
Horizontal Curve Combined with Non-Limited Sight-Distance Crest Vertical Curve	See Note 2	13	N/A
Horizontal Curve Combined with Limited Sight – Distance Crest Vertical Curve (K<43)	$V_{85} = 103.24 - (3576.51/R)$ (See Note 3)	22	0.74
Sag Vertical Curve on Horizontal Tangent	$V_{85} =$ Assumed Desired Speed	7	N/A
Vertical Crest Curve with Non-Limited Sight-Distance (K>43) on Horizontal Tangent	$V_{85} =$ Assumed Desired Speed	6	N/A
Vertical Crest Curve with Limited Sight-Distance (K<43) on Horizontal Tangent	$V_{85} = 105.08 - (149.69/K)$	9	0.60
Notes:			
1. V_{85} = 85 th percentile speed of passenger cars (km/hr); R = radius of curvature (m); K = rate of vertical curvature; G = grade (%)			
2. Use lowest speed of the speeds predicted from 1 or 2 (for the downgrade) and 3 or 4 (for the upgrade)			
3. In addition, check for conditions in Note 2 to be the lowest speed			
4. 1 mph = 1.61 km/hr and 1 ft = 0.3 m			

The two-lane rural highway design consistency methodology in the IHSDM uses these prediction equations, along with grade-limiting speeds predicted from Two Lanes with Passing

(TWOPAS) and speed adjustments based on acceleration and deceleration models, to estimate operating speeds along an alignment. The current version of IHSDM checks the 85th percentile speed profile against two consistency criteria. Color coding is used to indicate differences between 85th percentile speed and the designated design speed (or design speed as it is referred to in the IHSDM output). Green flags represent 85th percentile speeds that differ from the design speed by no more than 10 km/hr (6 mph). Yellow flags indicate a difference between 10 and 20 km/hr (6 and 12 mph). Red flags indicate a difference of more than 20 km/hr (12 mph). Similarly, the magnitude of the 85th percentile speed difference from each tangent to the succeeding curve is provided. Green flags represent 85th percentile speed changes of no more than 10 km/hr (6 mph). Yellow flags indicate a speed changes between 10 and 20 km/hr (6 and 12 mph). Red flags indicate speed changes of more than 20 km/hr (12 mph).

The literature review on design consistency demonstrates the key role of speed prediction in design consistency evaluations. Most speed prediction work has focused on two-lane rural highway horizontal curves (4-12) or urban street horizontal curves (13-16). The past research has also focused on the speed reduction from approach tangents to the mid-point of horizontal curves (11,17,18). There have been relatively few studies that have estimated operating speed models for rural horizontal tangents (12,19). Several speed modeling challenges have been explicitly identified by authors of published speed modeling literature through several speed-related research efforts (e.g., 20, 21, 22). These were briefly described in the introduction and are described in more detail below.

SPEED MODELING ISSUES AND CHALLENGES

Inclusion of the Posted Speed Limit in Operating Speed Model Estimation

Various authors have included posted speed limit in statistical models of operating speeds. For example, Fitzpatrick et al. (23) found that posted speed has the greatest influence on operating speed -- no other geometric design, traffic control, or roadside features were found to be significantly associated with 85th-percentile operating speeds. Fitzpatrick, et al. (24) also found the posted speed limit to have the greatest influence on speeds for suburban arterial horizontal curve and tangent segments. When the posted speed limit was included in the horizontal curve operating speed model, deflection angle and approach density were also statistically significant. When the posted speed limit was not included, median presence and several roadside land use variables were statistically significant in the 85th-percentile operating speed model. In the tangent segments model, only the posted speed limit was statistically significant when included in the model. However, if the posted speed limit was not included in the 85th-percentile operating speed model, then the lane width was found to be statistically significant.

Wang et al. (25) noted that since the design speed is usually based upon a proposed posted speed limit, geometric elements will be correlated with the designated design speed of the road. This was used as justification for investigating the influence of road environment characteristics on operating speeds without including the posted speed limit as a variable in the model. The authors also noted that most previous speed studies have focused on horizontal curves and not on tangent segments, because there are fewer geometric constraints on tangents when compared to horizontal curves. The explanatory variables in their model that were positively associated with 85th percentile speed include the number of lanes, presence of curb, and residential or other land uses compared to commercial adjacent land use. The explanatory

variables that were negatively associated with 85th percentile speed include increased density of roadside objects, driveway density of driveways, intersection density, the presence of an adjacent sidewalk, and the presence of on-street parking.

Drawing on concepts from applied econometrics modeling, the operating speed, posted speed issue is one of irrelevant variables, omitted variable bias, multicollinearity, and endogeneity. Four respective modeling scenarios and the likely practical outcomes are summarized in Table 2.

Table 2. Posted Speed Limit Modeling Scenarios and Possible Outcomes.

Modeling scenario	Likely outcome
Posted speed is included in the model specification, but is irrelevant to predicting speeds.	The parameter estimates are unbiased, but the standard errors increased. There is a higher level of uncertainty in model predictions.
Posted speed is excluded from the model, but is relevant to predicting speeds.	The model parameters are biased. The level of bias is proportional to the magnitude of correlation between posted speed and the variables included in the model. The influence of the roadway geometry on vehicle speeds is likely under- or over-estimated.
Posted speed is included in the model, but is correlated with other variables included in the model.	In the extreme case of perfect multicollinearity, the parameters cannot be estimated. In more typical cases, the individual parameter variances are inflated. This is not a problem, particularly in cases where the modeler is interested in prediction.
Posted speed is included in the model, but is not independent of the model disturbance (i.e., posted speed is not a truly independent variable).	The parameter estimates are biased because the posted speed variable violates the exogeneity assumption of ordinary least squares regression. The influence of all variables in the model on vehicle speeds is likely under- or over-estimated.

The scenarios and outcomes in Table 2 demonstrate that posted speed should not be excluded from the model due to correlation with other variables or to decrease the variance of parameter estimates (i.e., to increase statistical significance) because model parameters will be biased. It should only be excluded if there is reason to think that posted speed does not have any influence on the speed measure of interest. Whether or not posted speed is truly an independent (or exogenous) variable needs further exploration. To the authors' knowledge, this idea has not been addressed in existing speed modeling literature. Econometrics modeling literature suggests that if variables on the right-hand-side of a regression equation are not truly exogenous (i.e., the variables are related to the model disturbance), the modeler should consider specification and estimation of a simultaneous equations framework (26). This issue is explored later in this paper.

Free-flow Speeds

Published operating speed models have focused on using free-flow vehicles. Free-flow speeds are considered to be the speed at which the driver operates a vehicle when unconstrained by

other drivers or adverse weather conditions (e.g. snow or rain). Free-flow speeds are typically defined as having time headways of at least five or six seconds (23). However, including only free-flow speeds does not allow the researcher to include traffic characteristics as explanatory variables when estimating operating speeds. Previous researchers have included traffic characteristics in the speed model specification (27, 28), which provides insights to the range of speeds observed on a highway segment while still allowing evaluation of predicted free-flow speeds by setting traffic flow to a low value. This speed modeling practice also allows exploration of speed-highway geometry relationships at all points along the speed-flow curve.

Speed Aggregation

Tarris et al. (15) examined the impact of aggregating spot speeds versus using disaggregate level data on low-speed urban streets. The result of the analysis showed that the parameter estimate for degree of curvature is essentially the same for aggregate and disaggregate level data (-0.272 versus -0.265), however, the variability that the model explains is much greater when using aggregate level data. The improved goodness-of-fit (R^2) is a result of all individual drivers at a site being aggregated into one descriptive value for the site. Therefore, the variability in the speed distribution is being lost through data aggregation into a single descriptive value.

Park and Saccomanno (29) found similar results when comparing aggregate to disaggregate level speed data in model estimation. Estimating 85th percentile maximum speed reduction between adjacent horizontal tangents and curves as a function of the inverse horizontal curve radius at an aggregate level explained 63.8 percent of the variability in the data. Estimating the same outcome with individual speed data as a function of the inverse horizontal curve radius only explained 27.5 percent of the variability in the data. The authors explain that this result was not unexpected and confirms that information is lost through aggregation (i.e., ecological fallacy).

A possible solution is to model multiple measures of the speed distribution, including a measure of speed magnitude and a measure of speed variance. This approach has been successfully used by Shankar and Mannering (27), Ulfarsson et al. (28), and Porter and Mason (30). By exploring the relationship between multiple speed measures and geometry, the modeler knows if a change in 85th percentile speed was associated with a change in a mean measure of speed magnitude, a change in speed dispersion, or both. In addition, the systems modeling approach taken in the cited studies and used in this paper allows exploration of traditional speed-geometry relationships as well as contemporaneous inter-relationships between the speed measures themselves.

RESEARCH OBJECTIVE

The primary objectives of the speed-based models estimated in this research are to:

1. Estimate a system of simultaneous equations of the posted speed limit, mean speed, and speed deviation. Explicit consideration of the posted speed limit in the system of equations is addressed with the intent of providing some useful insights concerning its inclusion in speed prediction models;
2. Include hourly traffic flow in the speed modeling framework to determine if traffic flow is associated with various speed measures;

3. Estimate a model using the difference in the inferred design speed and the 85th-percentile speed as the dependent variable to illustrate its use an alternative design consistency evaluation method.

The research objectives are undertaken using data collected on both urban and rural two-lane, undivided highways. Such an approach permitted testing for speed differences in urban and rural operating environments through the statistical model specification.

METHODOLOGY

Two general models were specified in order to meet the research objectives: 1) a simultaneous equation model of posted speed, mean speed and standard deviation of speed (referred to as speed deviation for the remainder of the paper, and 2) a single-equation model of the difference between operating speed and inferred design speed. The systems model had the following general structure:

$$PSL = \alpha_{PSL} + X_{PSL}\beta_{PSL} + u_{PSL} \quad (1)$$

$$s = \alpha_s + X_s\beta_s + PSL\gamma_s + d\theta_s + u_s \quad (2)$$

$$d = \alpha_d + X_d\beta_d + PSL\gamma_d + s\theta_d + u_d \quad (3)$$

where:

PSL = posted speed limit;

s = mean speed;

d = speed deviation;

α = constant for posted speed limit, mean speed, and speed deviation, respectively;

X = vector of exogenous variables (geometric, traffic flow, etc.) for posted speed, mean speed, and speed deviation, respectively;

β = vector of estimable regression parameters for exogenous variables;

u = random disturbance term for posted speed limit, mean speed, and speed deviation, respectively;

γ = vector of estimable regression parameters for the posted speed limit endogenous variable; and,

θ = vector of estimable regression parameters for the mean speed and speed deviation endogenous variables.

An econometric approach to model estimation was taken. Three-stage least squares (3SLS) is a consistent and efficient estimator of the structures above provided all equations are identified (31, 32). The 3SLS estimator addresses endogeneity (i.e. $cov(PSL, u_s) \neq 0$, $cov(d, u_s) \neq 0$, $cov(PSL, u_d) \neq 0$, and $cov(s, u_d) \neq 0$) by using instruments for PSL, s, and d (i.e. variables that are correlated to the endogenous variables, but uncorrelated with the respective disturbances). In

other words, ordinary least squares regression results in biased parameter estimates when a dependent variable is included on the right-hand side of a regression equation. 3SLS provides an appropriate alternative in this context. It is also a full-information estimator, allowing error covariance (i.e., $\text{cov}(u_i, u_j) \neq 0$ for all i, j). Error covariance may result from shared unobservables between posted speed, mean speed and speed deviation. In other words, there are likely factors that influence the disturbance terms of posted speed, mean speed, and speed deviation. Accounting for these similarities improves the model efficiency (i.e., reduces the standard error of the parameter estimates). If the error variance-covariance matrix is diagonal (i.e. $\text{cov}(u_i, u_j) = 0$ for all i, j), then 3SLS offers no advantage over its limited information counterpart, two-stage least squares (2SLS). Additional details are provided by Greene (32).

The single-equation, operating speed-inferred design speed model took the following general form:

$$\Delta = \alpha_{\Delta} + X_{\Delta}\beta_{\Delta} + PSL\gamma_{\Delta} + u_{\Delta} \quad (4)$$

where:

Δ = delta speed = $IDS - V_{85}$;

V_{85} = 85th percentile speed;

IDS = inferred design speed;

α = constant for delta speed;

X = vector of exogenous variables for delta speed;

β = vector of estimable regression parameters for delta speed;

PSL = instrumented posted speed limit variable;

γ = estimable regression parameter for the posted speed limit;

u = random disturbance term for delta speed.

The single-equation model above is estimated with two-stage least squares, since PSL itself is also a function of geometric variables in the model (see discussion above).

DATA COLLECTION

Vehicle speed and roadway/roadside characteristics were collected at 79 sites on 8 roads in Pennsylvania and Virginia. Operating speeds were collected using Hi-Star Numetrics NC-97 traffic counters. It was determined by Poe et al. (13) that these sensors provided the best measure of vehicle speeds when compared to other commonly used data collection methods based on accuracy, effects on driver behavior, ease of installation, allocation of manpower, and the ability to match recorded vehicle speeds to the appropriate driver/vehicle data. A variety of specific geometric elements (e.g. horizontal curves, tangents, vertical curves) were sampled through the placement of sensors at points of interest. Sensors were located at the mid-point of horizontal curves and near the midpoint of horizontal tangents. On some horizontal tangents, data were collected at the low point of sag vertical curves or approximately near the point of minimum sight distance on crest vertical curves. Speeds were not collected in close proximity to any traffic control devices requiring vehicles to stop (e.g., signals or STOP signs).

Roadway geometry data were collected using as-built drawings. On-site inspection was used to obtain information about roadside land-use, pavement marking presence, and presence of on-street parking. The geometric features of each roadway was also input into the Interactive Highway Safety Design Model (IHSDM) to determine the available stopping sight distance at each site where speed data were collected. The descriptive statistics for the continuous variables of interest are shown in Table 3 and the categorical descriptive statistics are shown in Table 4.

The inferred design speed was established using the methodology that can be found in Donnell et al. (22). The inferred design speed is the minimum speed for which all critical design-speed-related criteria are met at a particular location. The inferred design speed can only be applied to roadway elements that are based on design speed (e.g. horizontal curvature, vertical and horizontal sight distance). The inferred design speed will be equal to or greater than the designated design speed of the roadway, if minimum or above-minimum design criteria are used for a designated design speed. However, there are instances where the inferred design speed may be less than the designated design speed. When below-minimum design criteria are used for a designated design speed, the inferred design speed will be less than the designated design speed. Additionally, because design speed-related criteria have evolved over time, or because some existing roadway were constructed prior to the development of geometric design criteria, it is possible that there are instances where the inferred design speed will be less than the designated design speed. The inferred design speed was calculated for each individual site and was used in the delta speed model. The maximum value of inferred design speed was limited to 161 km/h (100 mph) on long tangent segments.

Table 3. Descriptive Statistics of Continuous Variables.

Variable	N	Min	Max	Mean	SD
Mean operating speed in mph (km/hr)	79	24.3 (39.0)	56.9 (91.5)	41.8 (67.3)	8.6 (13.9)
85 th percentile speed in mph (km/hr)	79	32 (51.5)	62.6 (100.7)	47.6 (76.6)	8.8 (14.2)
Speed deviation in mph (km/hr)	79	3.5 (5.6)	9.3 (15.0)	6.72 (10.8)	1.4 (2.2)
Posted speed limit in mph (km/hr)	79	25 (40.2)	55 (88.5)	42.9 (69.0)	10.5 (16.9)
Inferred design speed in mph (km/hr)	79	34.1 (54.9)	100 (160.9)	58.8 (94.6)	18.2 (29.3)
Delta speed in mph (km/hr)	79	-17 (-27.4)	60.1 (96.7)	11.1 (17.9)	17.3 (27.8)
Hourly traffic volume (vph)	79	12.6	439	122.92	113.25
Heavy vehicle percentage (%)	79	0.8	28	7.50	5.80
Degree of curve (degrees)	79	0	14	4.23	4.59
Superelevation	79	-3	8	3.48	3.11
Horizontal curve length in ft (m)	79	0	1419 (432)	266 (81)	321 (98)
Tangent length in ft (m)	79	0	4849 (1478)	386 (118)	967 (295)
Grade (%)	79	-9.76	10.64	0.63	4.57
Rate of vertical curvature	79	0	312.5	43.43	65.84
Access points within 500 ft of site (#)	79	0	13	3.82	3.13
Access points within 1000 ft of site (#)	79	0	25	7.37	5.60
Available sight distance in ft (m)	79	303 (92)	1842 (561)	796 (243)	400 (122)
Clear zone width in ft (m)	79	4 (1.2)	30 (9.1)	15.8 (4.8)	8.7 (2.6)
Total shoulder width in ft (m)	79	0 (0)	10 (3.0)	5.8 (1.8)	2.1 (0.6)

Note: A value of zero for the degree of curve and horizontal curve length indicates that the roadway segment is a tangent section. A value of zero for the tangent length indicates that the roadway segment is on a horizontal curve.

The descriptive statistics show that 29 percent of the data collection sites were urban and 71 percent of the data collection sites were rural. The descriptive statistics also show that there is a wide range in the values of each of the variables that were considered in the analyses. However, there were very few observed adjacent land uses of school, agriculture, and commerce. As such, these land use categories were combined into a single category for use in the model estimations described below. Observed mean and 85th percentile operating speeds include all observed speeds, as opposed to only free-flow speeds. It should be noted that free-flow speeds can be estimated using the proposed modeling approach by inputting low traffic flow levels in the model.

Table 4. Descriptive Statistics of Categorical Variables.

Variable	Categories	Frequency	Percent
Horizontal Curve Direction	Horizontal Tangent	33	41.8 %
	Horizontal Curve to Left	25	31.6 %
	Horizontal Curve to Right	21	26.6 %
Vertical Curve Type	Vertical Tangent	42	41.8 %
	Crest Vertical Curve	23	29.1 %
	Sag Vertical Curve	14	17.7 %
Adjacent Land Use	Wooded	26	32.9 %
	Residential	38	48.1 %
	Industrial	8	10.1 %
	School	3	3.8 %
	Agricultural	3	3.8 %
	Commercial	1	1.3 %
Curb and Gutter	Present	25	31.6 %
	Absent	54	68.4 %
Area Type	Rural	56	70.9 %
	Urban	23	29.1 %
Median / Turning Lane	Present	13	16.5 %
	Absent	66	83.5 %
At-Grade Rail Crossing	Present	7	8.9 %
	Absent	72	90.1 %
On-Street Parking	Present	10	12.7 %
	Absent	69	87.3 %

ANALYSIS AND DISCUSSION

Simultaneous Equation Estimation

The 3SLS model for the posted speed limit, mean speed, and speed deviation is shown in Table 5. The form of the model specification is as follows:

$$PSL = \alpha_{PSL} + X_{PSL}\beta_{PSL} + u_{PSL} \quad (5)$$

$$s = \alpha_s + X_s\beta_s + PSL\gamma_s + u_s \quad (6)$$

$$d = \alpha_d + X_d \beta_d + PSL \gamma_d + s \theta_d + u_d \quad (7)$$

The only difference between the model specification shown in equations (5) through (7) and the general model structure shown in equations (1) through (3) is the speed deviation (d) does not appear in the mean speed (s) equation (6). As such, the mean speed is not affected by speed deviation, but speed deviation is affected by mean speed. The posted speed limit instrumented variable is statistically significant in the mean speed and speed deviation equations (6) and (7).

Most of the variables that are statistically significant in the posted speed limit equation are consistent with engineering practice and the Manual on Uniform Traffic Control Devices (MUTCD). The 2003 version of the MUTCD (33) states that the posted speed limit should be within 5 mph (10 km/hr) of the 85th percentile speed. The MUTCD also presents other factors that may be considered when establishing a posted speed limit. These include:

- Road characteristics, shoulder condition, grade, alignment, and sight distance;
- The pace speed;
- Roadside development and environment;
- Parking practices and pedestrian activity;
- Reported crash experience for at least a 12 month period.

The estimated model for posted speed in Table 5 shows that grade, roadside development (residential and industrial land uses), and the presence of on-street parking are all statistically significant and negatively correlated with the posted speed limit. The number of nearby access points, the presence of curb and gutter, grade, and the presence of a median or turning lane are associated with reductions in the posted speed limit. The hourly traffic volume is positively associated with the posted speed limit. Horizontal alignment features (e.g. radius, superelevation rate) and available stopping sight distance were not statistically significant in the model.

The explanatory variables in the posted speed equation can likely be considered as “surrogates” for the roadway functional class, with the base condition being a rural arterial (posted speed 55 mph or 90 km/hr). The largest reductions to the posted speed limit are associated with the presence of on-street parking and the presence of a median or turn lanes. These variables correspond to typical characteristics of low-speed urban streets. The presence of curb and gutter also has an influence on the posted speed limit, and is typically present only on low-speed urban streets. The number of access points may also be a surrogate for functional class, as arterials provide a high level of mobility and are therefore more likely to have reduced levels of access when compared to collectors or local streets. Finally, the vertical grade may also be a surrogate for functional class since lower functional class roadways are associated with higher limiting values of grade in geometric design criteria.

From the 3SLS shown in Table 5, it was shown that the geometric design features on two-lane roads are not correlated with the posted speed limit (with the exception of vertical grade). Therefore, the posted speed limit should not be ignored as a predictor of operating speed based on its perceived association with the roadway geometry.

Table 5. 3SLS Model of Posted Speed, Mean Speed, and Speed Deviation.

Variable	Estimated Coefficient	Standard Error	t-statistic	p-value
<i>Equation 1: Posted Speed Limit</i>				
Constant	54.02 (86.94)	0.84 (1.36)	64.10	< 0.001
Number of access points within 1000 ft (305 m) of data collection location	-0.72 (-1.15)	0.09 (0.15)	-7.80	< 0.001
Hourly traffic volume (veh/hr)	0.02 (0.03)	0.004 (0.006)	4.34	<0.001
Residential adjacent land use indicator (1 if residential; 0 otherwise)	-4.51 (-7.26)	1.21 (1.95)	-3.73	<0.001
Industrial adjacent land use indicator (1 if industrial; 0 otherwise)	-6.49 (-10.45)	1.59 (2.56)	-4.08	< 0.001
Indicator for curb and gutter (1 if present; 0 otherwise)	-6.37 (-10.25)	1.63 (2.62)	-3.91	<0.001
Grade (percent)	-0.20 (-0.31)	0.09 (0.14)	-2.22	0.026
Indicator for on-street parking (1 if present; 0 otherwise)	-12.56 (-20.21)	1.95 (3.13)	-6.45	< 0.001
Presence of median or turning lane (1 if present; 0 otherwise)	-7.94 (-12.78)	1.80 (2.90)	-4.41	< 0.001
Number of observations = 79 RMSE = 3.456 R ² =0.891				
<i>Equation 2: Mean Speed</i>				
Constant	18.20 (29.29)	2.31 (3.71)	7.89	< 0.001
Posted speed limit*	0.60 (0.60)	0.04 (0.04)	14.87	< 0.001
Total shoulder width	0.33 (1.74)	0.15 (0.79)	2.21	0.027
Number of access points within 1,000 ft (305 m) of location	-0.29 (-0.47)	0.07 (0.12)	-3.92	< 0.001
Presence of median or turning lane (1 if present; 0 otherwise)	-3.22 (-5.17)	1.03 (1.66)	-3.12	0.002
Presence of at-grade rail crossing within 500 ft (152 m) (1 if present; 0 otherwise)	-5.64 (-9.08)	1.13 (1.82)	-4.97	< 0.001
Left-hand curve indicator (1 if left-hand curve; 0 otherwise)	-1.41 (-2.26)	0.69 (1.11)	-2.04	0.041
Crest vertical curve indicator (1 if crest-vertical curve; 0 otherwise)	-1.18 (-1.89)	0.66 (1.07)	-1.77	0.076
Number of observations = 79 RMSE = 2.803 R ² =0.893				
<i>Equation 3: Speed Deviation</i>				
Constant	7.45 (12.00)	0.87 (1.39)	8.60	< 0.001
Posted speed limit*	0.10 (0.10)	0.03 (0.03)	3.34	0.001
Mean speed **	-0.09 (-0.09)	0.04 (0.04)	-1.98	0.048
Hourly traffic volume (veh/hr)	-0.01 (-0.02)	0.001 (0.002)	-9.14	< 0.001
Grade (percent)	-0.08 (-0.12)	0.02 (0.04)	-3.40	0.001
Wooded adjacent land use indicator (1 if wooded; 0 otherwise)	-1.05 (-1.69)	0.29 (0.46)	-3.63	<0.001
Left-hand curve indicator (1 if left-hand curve; 0 otherwise)	-0.47 (-0.75)	0.21 (0.34)	-2.19	0.028
Percent heavy vehicles in traffic stream (percent)	0.05 (0.09)	0.03 (0.05)	1.60	0.110
Number of observations = 79 RMSE = 0.849 R ² = 0.618				
*Posted speed limit is an instrumented variable. **Mean speed is an endogenous variable in the speed deviation equation.				

The mean speed equation estimated using 3SLS is also shown in Table 5. As expected, the posted speed limit is statistically significant and positively associated with the mean speed. A one mph increase in the posted speed limit is associated with a 0.6 mph (0.6 km/hr) increase in the expected mean speed. A one foot (0.3 m) increase in the total shoulder width (including paved and unpaved shoulder) is associated with a 0.33 mph (1.74 km/hr) increase in the expected mean speed. An one-unit increase in the number of access points within 1,000 ft of the site is associated with a 0.29 mph (0.47 km/hr) reduction in the mean speed. The presence of a median or turning lane is associated with a reduction in mean speed by 3.22 mph (5.17 km/hr) when compared to the baseline of no median or turn-lane present. Seven of the data collection sites were within 500 ft (152 m) of an at-grade railroad crossing. The presence of this at-grade railroad crossing was associated with a reduction in mean speed of 5.64 mph (9.08 km/hr). The presence of a left-hand curve, when compared to right-hand curves and horizontal tangents is associated with a 1.41 mph (2.26 km/hr) reduction in the mean speed. The presence of a crest vertical curve is associated with a 1.18 mph (1.89 km/hr) reduction in mean speed, compared to vertical tangents and sag vertical curves.

The speed deviation equation is also shown in Table 5. The hourly traffic volume has the strongest association with speed deviation. Other exogenous variables that are statistically significant in the speed deviation equation are: vertical grade, wooded adjacent land use, the presence of curb and gutter, the presence of a left-hand curve, and the percentage of heavy vehicles in the traffic stream. The wooded adjacent land use variable captures the effect of roadside access on speed deviation. It was expected that commercial, industrial, and residential land uses would result in a higher deviation in speeds. The access density variables, however, were correlated to the land use variables and could not be included in the model.

An increase of 100 vph in the hourly traffic volume is associated with a decrease in speed deviation by 1.2 mph (1.9 km/hr). This is intuitive since as traffic volume increases, the opportunity for selecting a speed decreases. Higher traffic volumes in this case lead to a more uniform flow. A one percent increase in grade is associated with a 0.08 mph (0.02 km/hr) decrease in speed deviation. A wooded adjacent land use is associated with a 1.05 mph (1.69 km/hr) decrease in speed deviation when compared to other land uses (residential, industrial, etc.). This adjacent land use captures the effect of access points. Since a rural wooded land use likely has a limited number of access points, the flow is more uniform as a result of fewer turning vehicles. The presence of a left-hand horizontal curve is associated with a 0.47 mph (0.75 mph) reduction in speed deviation when compared to right-hand curves and horizontal tangents. A one percent increase in the percentage of heavy vehicles in the traffic stream is associated with a 0.05 mph (0.09 km/hr) increase in the speed deviation.

From an application perspective, the equations resulting from the 3SLS model shown in Table 5 can be used in combination to estimate a distribution of speeds at a given site. The 85th percentile speed is typically estimated as the mean speed plus one standard deviation. This approach allows the analyst to determine a range of speeds and also considers that the standard deviation of speed will change between sites. These models not only allow for the consistency in an operating speed measure to be estimated, but these models also permit the standard deviation to be standard deviation of speed to be estimated between sites.

Delta Speed Model Estimation

The delta speed model was also estimated based on the general model form shown in equation (4) to consider an alternative measure of design consistency for two-lane highways. This model is applicable to both horizontal curves and horizontal tangent sections, and the primary interest is to determine if the inferred design speed is greater than or less than the 85th percentile speed at a site. The direction of the effect of explanatory variables on delta speed is not necessarily an indicator of design consistency. However, significant changes in the delta speed estimate between adjacent roadway segments (i.e., tangent to curve) may indicate a design inconsistency. This issue is discussed in more detail after presenting the delta speed model, which is shown in Table 5.

The results show that for every one degree increase in the degree of curve, a reduction in the delta speed of 1.86 mph (2.98 km/hr) can be expected. A unit increase (one percent) in the superelevation rate is associated with a 1.07 mph (1.72 km/hr) reduction in the delta speed. A 5 mph (8 km/hr) increase in the posted speed limit is associated with a 1.13 mph (1.13 km/hr) reduction in delta speed. The logarithm of the available stopping sight distance is associated with an increase in the delta speed. The rate of vertical curvature is also associated with an increase in delta speed. An increase of 100 in the rate of vertical curvature is associated with an increase of 3.6 mph (5.8 km/hr) in delta speed. For a unit increase in the number of access points within 1000 feet (305 m) of the speed data collection site, a 1.1 mph (1.8 km/hr) increase in delta speed is expected. Finally, widening the clear zone is also associated with an increase in delta speed. For each one foot (0.3 m) increase in the clear zone width, a 0.26 mph (0.42 km/hr) increase in delta speed is expected.

Sample Illustration of Estimated Speed Prediction Models

The study segment is a two-lane, rural principal arterial in Pennsylvania, approximately 1.4 miles (2.3 km) in length. There are seven simple horizontal curves with radii ranging from 716 feet (218 m) to 1432 feet (436 m). There are five crest vertical curves. When the roadway was originally built in 1925, superelevation was provided on horizontal curves although no design speed was designated. A subsequent project (completed in 2004) was undertaken with a designated design speed of 60 mph (100 km/hr) and increased the superelevation at each horizontal curve. The vertical alignment has not been altered since construction in 1925. The available sight distance for one crest vertical curve located near the middle of the study segment is less than the criteria associated with a 60 mph (100 km/hr) design speed. The maximum grade within the segment is seven percent. The posted speed is 55 mph (90 km/hr) but there are no speed limit signs within the study segment.

The typical cross section includes one travel lane in each direction and a four foot paved shoulder. The clear zone width ranged from 4 to 30 feet (1.2 to 9.1 m) along the alignment. The adjacent land use is wooded and the average annual daily traffic for the study segment is approximately 2,500 vehicles per day, of which ten percent is heavy vehicles.

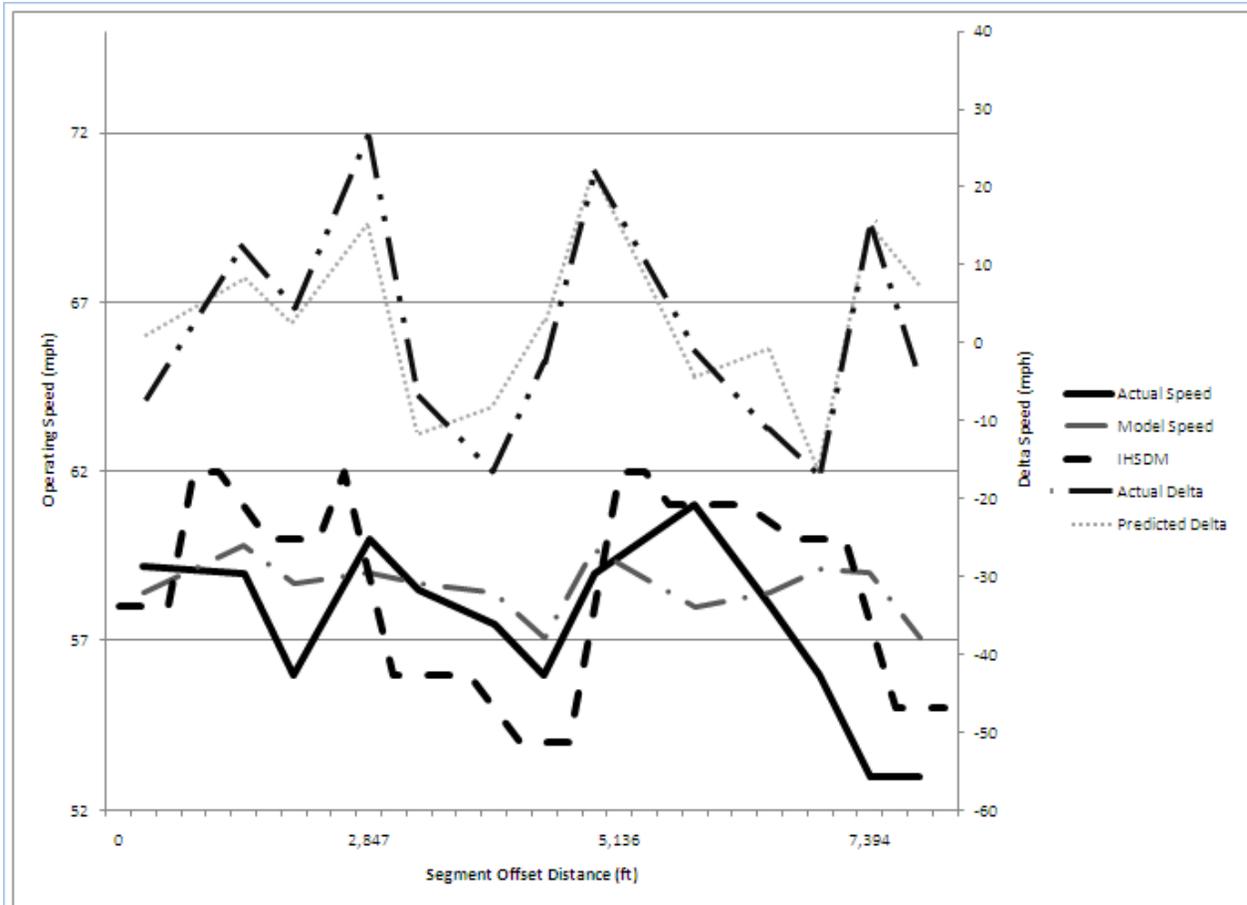
Table 6. 2SLS Model for Delta Speed.

Variable	Estimated Coefficient	Standard Error	t-statistic	p-value
Constant in mph (km/hr)	-88.44 (-111.15)	12.69 (17.27)	-6.97	< 0.001
Posted speed limit* in mph (km/hr)	-0.23 (-0.23)	0.13 (0.13)	-1.81	0.071
Logarithm of available stopping sight distance	16.31 (26.25)	1.96 (3.15)	8.34	< 0.001
Degree of curve	-1.86 (-2.98)	0.23 (0.37)	-8.06	< 0.001
Rate of vertical curvature	0.04 (0.06)	0.01 (0.02)	2.76	0.006
Number of access points within 1,000 ft (305 m) of location	1.10 (1.77)	0.19 (0.31)	5.74	< 0.001
Superelevation rate in percent	-1.07 (-1.72)	0.37 (0.59)	-2.89	0.004
Clear zone width	0.26 (0.42)	0.10 (0.17)	2.50	0.012
Number of observations = 79 RMSE = 7.43 R ² = 0.813 *The posted speed limit is an instrumented variable. The instrument was developed using the posted speed equation in Table 4.				

At numerous locations, sight distances are limited by the vertical alignment and horizontal alignment in combination with lateral obstructions, mostly cut slopes. Sight distance restrictions translate to inferred design speeds as low as 39 mph (63 km/hr). The inferred design speeds for horizontal curves range from 48 to 61 mph (77 to 98 km/hr). An advisory speed of 40 mph (65 km/hr) is posted at 4 horizontal curves and an advisory speed of 50 mph (80 km/hr) is posted at 2 other curves.

Figure 1 shows a speed profile plot for the study segment. The observed 85th percentile speed is plotted along with the estimated 85th percentile speed (mean speed estimate plus standard deviation estimate from Table 5) and the estimated operating speed that is output from the IHSDM design consistency module. Both speed prediction models appear to match the observed data well. Table 7 shows the observed 85th-percentile speed at 13 locations on along the sample alignment. The estimated 3SLS model appears to more closely predict the observed speeds than the IHSDM design consistency module when collectively considering all 13 speed measurement locations. This is based on the average and average squared prediction error.

The observed and estimated delta speeds are also plotted in Figure 1. The delta speed model appears to have two implications. The first is that negative values (or even sharp drops in the delta speed that are still positive) seem to indicate that a reduction in speed will be observed at that location of the alignment, and speed increases will be found where large positive values (or increasing delta speed occurs). The second implication is that the operating speed can be larger than the inferred design speed, while traditional models will consider the roadway to have a “good” design consistency. The segment shown in Figure 1 had no flags in the design consistency output from the IHSDM. However, as can be seen in Figure 1, at two locations the operating speed is actually 17 mph (27 km/hr) greater than the inferred design speed. This relationship is not determined from traditional design consistency methods. In the policy review module, the “inferred design speed” of roadway elements can be checked to conform to the policy as related to a designated design speed. Even if the elements meet the criteria associated with a designated design speed, the operating speed may still exceed the inferred design speed.



Notes: 1 mph = 1.609 km/hr; 1 ft = 0.304 m

Figure 1. Various speed measures on an example roadway segment

Theoretically, the delta speed as defined in this paper should not be an indicator of good, fair, or poor design consistency if the difference between the inferred design speed and the 85th-percentile operating speed is positive, regardless of magnitude. At these locations, vehicle operating speeds are lower than the design speed that was used to design the geometric features along the roadway. However, when the delta speed measure is negative, this indicates that the 85th-percentile speed exceeds the inferred design speed of the roadway. In such cases, the design speed concept can be used as a measure of consistency. Large negative values for the delta speed are shown in Figure 1 at approximately 4,000 and 7,000 foot (1,219 and 2,134 m) offsets along the alignment. The delta speed in both cases is -17 mph (-27 km/hr). At both locations, below minimum horizontal curve radii, for a designated design speed, were constructed. Although advance curve warning signs with speed advisory placards are provided in advance of these curves, they are not likely having the desired effect. The current version of the ISHDM design consistency module does not flag either of these locations as fair or poor design consistency. Although a safety analysis was undertaken, future research should be directed as determining if the delta speed measure proposed in this model is a viable design consistency and safety assessment tool.

Table 7. Observed 85th-Percentile Speeds, ISHDM Speed Predictions, and Speed Estimates from Present Study.

Segment Offset ft (m)	Observed Speed mph (km/hr)	IHSDM Speed mph (km/hr)	Model Speed mph (km/hr)	IHSDM – Observed mph (km/hr)	Model – Observed mph (km/hr)	IHSDM Square Error mph ² (km/hr) ²	Model Square Error mph ² (km/hr) ²
255	59.2 (95.3)	58 (93)	58.6 (94.3)	-1.2 (-1.9)	-0.61 (-0.98)	1.44 (3.73)	0.37 (0.96)
900	59 (95)	62 (100)	59.9 (96.4)	2.95 (4.83)	0.90 (1.45)	8.70 (23.31)	0.81 (2.10)
1725	56 (90)	60 (97)	58.7 (94.5)	4.0 (6.4)	2.70 (4.35)	16 (41.44)	7.28 (18.88)
2847	60 (97)	59.8 (96.2)	57.9 (93.2)	-0.19 (-0.32)	-2.14 (-3.44)	0.04 (0.10)	4.58 (11.86)
3710	58.5 (94)	56 (90)	57.1 (91.9)	-2.5 (-4.0)	-1.43 (-2.30)	6.25 (16.19)	2.04 (5.30)
4005	57.5 (93)	55.3 (89)	57.9 (93.2)	-2.2 (-3.5)	0.40 (0.64)	4.93 (12.54)	0.16 (0.41)
4283	56 (90)	54 (87)	57.3 (92.3)	-2.0 (-3.2)	1.33 (2.14)	4 (10.36)	1.77 (4.58)
4947	59 (95)	59.8 (96.2)	59.5 (95.7)	0.82 (1.29)	0.45 (0.71)	0.67 (1.66)	0.20 (0.50)
5821	61 (98)	61 (98)	57.7 (92.9)	0 (0)	-3.30 (-5.31)	0 (0)	10.90 (28.20)
6366	58 (93)	60.8 (97.8)	58.0 (93.4)	2.8 (4.5)	0.00 (0.00)	7.84 (20.31)	0.00 (0.00)
6924	56 (90)	60 (97)	57.9 (93.2)	4.0 (6.4)	1.94 (3.12)	16 (41.44)	3.78 (9.75)
7394	53 (85)	57.5 (92.5)	57.8 (93.0)	4.5 (7.2)	4.75 (7.64)	20.3 (52.45)	22.59 (58.44)
7659	53 (85)	55 (89)	55.5 (89.3)	2 (3.2)	2.47 (3.99)	4 (10.36)	6.11 (15.93)
Sum				12.96 (20.9)	7.46 (12.01)	168 (234)	56 (157)
Average				1.00 (1.61)	0.57 (0.92)	0.99 (17.99)	0.33 (12.07)
Minimum				-2.5 (-4.02)	-3.30 (-5.31)	0.00 (0.00)	0.00 (0.00)
Maximum				4.5 (7.24)	4.75 (7.64)	20.3(52.45)	22.59 (58.44)

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

Based on the present study, the 3SLS model indicates that the posted speed limit should not be ignored as an explanatory variable in operating speed prediction models on two-lane highways. The posted speed limit does not appear to be correlated with the geometric features of the roadway. Rather, it is apparently related to variables that are more closely linked with the roadway functional class or the area type. As a result, an instrumented posted speed limit variable was included in the mean speed and speed deviation models. The results of these models indicate that the posted speed limit is associated with both the mean speed and standard deviation. But unlike some published operating speed literature, several other roadway and roadside features along the alignment are statistically significant in the model estimation and all have plausible signs. An interesting finding from the simultaneous equations model estimation is that many of the explanatory variables for the geometric design features did not enter the model as continuous variables (e.g., degree of curve, rate of change in vertical curve); rather, they entered the model as indicator variables. Future research should be undertaken using additional data from two-lane rural highways to confirm the speed-related associations found in the present study.

A recursive relationship was found between the mean speed and speed deviation in the speed deviation equation, however, the reverse was not true. In other words, the mean speed affects speed deviation, but speed deviation does not affect mean speed. It is recommended that future operating speed prediction models on two-lane highways consider the possible endogenous relationship between mean speed and speed deviation. Explicit consideration of

speed deviation permits consideration of the entire speed distribution in a modeling framework. Free-flow speeds can also be considered using the econometric modeling methods included in the present study by inputting low hourly traffic flow rates in the model and thus parallels between the present study and existing published operating speed research can be drawn. Because the hourly traffic flow rate was not statistically significant in all equations, future research should consider aggregating speeds over multiple time-periods at individual sites to determine the effect of time-variant flow rates.

The delta speed model was estimated to predict the difference between the inferred design speed and the 85th-percentile operating speed. This model is intended to be used as a supplement to the current design consistency practices. The current design consistency methods are able to estimate speed differences between adjacent elements, and to compare predicted operating speeds to designated design speeds. However, current design consistency practice does not consider the inferred design speed. The magnitude of the delta speed measure seems to be an indicator of how drivers select an operating speed in relation to the geometric features present along the roadway. Future research should explore the relationship between delta speed and accident frequency/severity.

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