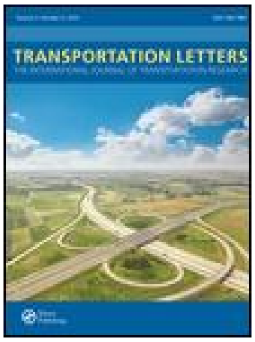

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Models of vehicle operating speeds along two-lane rural highway transition zones: panel and multilevel modeling approaches

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ABSTRACT: Transition zones are defined as locations where the posted speed limit changes from high- to low-speed. On high-speed two-lane rural highways, transition zones are often encountered when the roadway approaches a built-up area. The purpose of this study was to collect operating speed, roadway, roadside, traffic control, and land use data along two-lane rural highway transition zones in central Pennsylvania. These data were used to estimate passenger car operating speed models, recognizing the hierarchical nature of the data-generating process. The results showed that a three-level model could capture site-level speed variance that could not be captured in a panel data modeling framework; however, the parameter estimates and standard errors were very similar when comparing the model estimation results. It was also found that the presence of horizontal curves, presence of warning signs, the presence of curb, and increased access density were associated with reduced vehicle operating speeds. Increasing the lane width, shoulder width, and lateral clearance to obstructions was associated with increases in vehicle operating speeds. The models estimated in this paper could be used as a starting point to develop transition zone design guidelines.

KEYWORDS: vehicle operating speed, rural highway, transition zones, speed limit

1. INTRODUCTION

Speed is a complex issue. When selecting a speed on highways, drivers are influenced by a variety of information sources related to the roadway, roadside, and surrounding environment. The geometric features, surrounding land use, community context, and aesthetics all may affect drivers' perception of the appropriate speed and associated risk. When a rural highway approaches a built-up area, the posted speed limit often changes from one that encourages high vehicle operating speeds to one where lower operating speeds are expected. In addition, the context changes from one that is primarily for vehicular movement (i.e., mobility) to a multi-user and multi-purpose context where facilities for parking, pedestrians, and other non-motorized users may be present.

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A transition zone is a longitudinal segment of roadway where drivers are encouraged and expected to reduce their operating speed to one suitable for the environment they are entering. Failure to reduce operating speeds in the low-speed zone of a built-up area may result in speeds that are neither safe nor acceptable to the adjacent community. Donnell and Cruzado (2008) provided several examples of speed profiles along two-lane rural highway transition zones in Pennsylvania. In no case was the reduction in the mean or 85th-percentile operating speed commensurate with the change in the posted speed limit.

Published research and existing geometric design policies provide an extensive amount of information and guidance related to the design, safety, and operational performance of high-and low-speed highways; however, similar information does not exist for transition zones that connect these two distinctly different operating environments. Although some roadway, roadside, and land use features along the transition zone may be providing important cues to drivers to reduce their operating speeds, there may be characteristics present that do not reinforce the speed reduction message.

The purpose of the present study was to collect roadway, roadside, traffic control, and land use characteristic data along two-lane rural highway transition zones, and

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Figure 1. Example of a Transition Zone with a Reduced Speed Ahead Sign

to estimate statistical models of vehicle operating speeds along these highway sections. These models may serve as an important first-step in determining which highway features are associated with driver speed choice in transition zones. Understanding the features that influence speeds in transition zones may then be used to inform future research that ultimately leads to the development of guidance that promotes vehicle operating speed reductions commensurate with changes in the posted speed limit.

2. LITERATURE REVIEW

This literature review is organized into three sections. The first is a synthesis of speed transition zone research. Because the literature on this topic is limited, published literature related to operating speed models on two-lane rural highways and low-speed urban streets is also synthesized. Statistical methods used to estimate operating speed models are noted throughout the review.

2.1 Operating Speeds in Transition Zones

Cruzado and Donnell (2010) estimated ordinary least squares (OLS) linear regression and two-level hierarchical linear models of operating speed changes along two-lane rural highway transition zones using data from 20 sites in Pennsylvania. The dependent variable was defined as the difference in vehicle operating speeds between a "Reduced Speed Ahead" warning sign and the regulatory sign indicating the lower posted speed limit. These signs marked the limits of the speed transition zone. The authors found that higher vehicle operating speeds entering the transition zone were associated with greater speed reductions within the transition zone. Reductions in the lane width, shoulder width, and lateral clearance within the transition zone were associated with greater speed reductions in the transition zone. An increase in the number of driveways was associated with increased speed reductions in transition zones. The presence of curb and gutter and several warning signs within the transition zone was associated with reductions in the operating speed within the transition zone. The presence of a horizontal curve within the transition zone was associated with a speed reduction in the transition zone when compared to tangent roadway segments. Finally, increasing the length of the transition zone was associated with greater mean operating speed reductions in the transition zone. From a modeling perspective, many of the parameter estimates in the OLS linear regression and multi-level models were similar in magnitude, but the standard errors in the multi-level model were larger than those in the OLS linear regression model.

Stamatiadis et al. (2004, 2006) addressed the need to develop geometric design criteria for transition zones, indicating that flexibility in applying design criteria is needed in an attempt to reduce vehicle operating speeds in these zones. Design flexibility was defined as the use of criteria that are outside the range of values associated with a particular design speed, or use of design exceptions when limiting values of controlling criteria cannot be met for a specific project. At three locations where the roadway transitioned from a high-speed rural area to a built-up community, design flexibility was employed in a roadway improvement project in an attempt to reduce vehicle operating speeds prior to entering the built-up rural community. The design flexibility applications employed in each of the three projects included a combination of the following: reconstructing in a constrained right-of-way, introducing curb-and-gutter in the transition zone, innovative intersection design, reducing design elements, reducing the roadway cross-section, or installing roadside barriers to shield obstacles within the clear zone. A before-after crash analysis indicated that applying flexible design concepts generally resulted in a lower crash frequency and rate. Additionally, the authors found that vehicle operating speeds did not change significantly after applying flexible design applications along the transition zone. The authors concluded that increased attention to the design of transition zones between rural and built-up areas is needed to inform the driver of the change in the roadway context.

2.2 Operating Speed Models for Two-lane Rural Highways

Operating speed literature related to two-lane rural highways is vast. The principal purpose of this literature is to provide

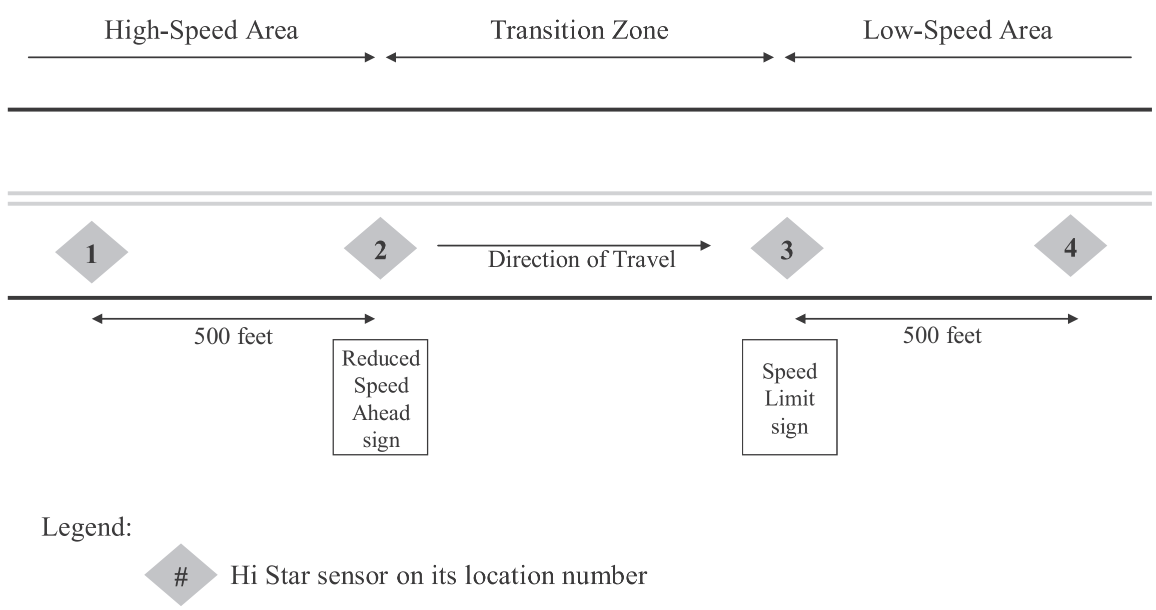

Figure 2. Representation of the Location of Speed Sensors

speed prediction models for use in geometric design consistency evaluations. While these models are not directly applicable to speed reductions in high-to-low speed transition zones, the association between speed and various roadway, roadside, and land use features of the roadway may provide some useful information to aid practitioners in designing transition zones that produce reduced vehicle operating speeds. The published literature related to the effects of highway features on vehicle operating speeds along two-lane rural highways indicates that there is consensus that increasing the degree of curve (or decreasing the curve radius) is associated with a decrease in vehicle operating speed on horizontal curves (Glennon et al. 1985; Lamm and Choueiri 1987; Krammes et al. 1995; Passetti and Fambro 1999; Fitzpatrick et al. 2000). Each of these past studies used the 85th-percentile from the speed distribution as the dependent variable in an OLS linear regression model. While aggregating speeds from individual drivers at a point location produced an improved statistical fit to the data, Park and Saccomanno (2006) noted that such an approach results in an ecological fallacy.

More recently, McFadden and Elefteriadou (2000) and Misaghi and Hassan (2005) estimated OLS linear regression models of the speed reduction observed by drivers between the approach tangent and a horizontal curve. While these efforts both concluded that increasing the degree of curve (or decreasing the radius of curve) is associated with an increased speed reduction between an approach tangent and horizontal curve, speed measurements recorded for the same vehicle at two different points in time are not independent as assumed in OLS linear regression. Collectively, these studies found that increasing the length of the approach tangent, increases in the approach tangent speed, steeper vertical grades, intersection presence, and increased curve deflection angles increase speed reductions between the approach tangent and horizontal curve. Misaghi and Hannan (2005) found that increasing the shoulder width is associated with a decrease in the speed reduction between the approach tangent and horizontal curve.

Figueroa and Tarko (2005) used a panel data approach to estimate models of vehicle operating speeds on two-lane rural highways. The panel was created by computing percentile speeds from the observed speeds measured at each site, and thus considered the multiple observations made on individual vehicles included in the sample. The authors also considered a variety of possible explanatory variables in models estimated for both tangent and curved roadway segments. The authors found that increasing the vertical grade and the number of access points on a tangent was associated with lower operating speeds. Increasing the available sight distance and shoulder width on tangents was associated with increases in the operating speed. Decreasing the posted speed limit or the horizontal curve radius was associated with lower vehicle operating speeds on tangent segments. The presence of an at-grade intersection was associated with lower vehicle operating speeds on tangent segments. On horizontal curves, increasing the available sight distance and the superelevation was associated with increases in the expected operating speed. Increasing the access density and the degree of curve was associated with a decrease in the expected vehicle operating speed on curves.

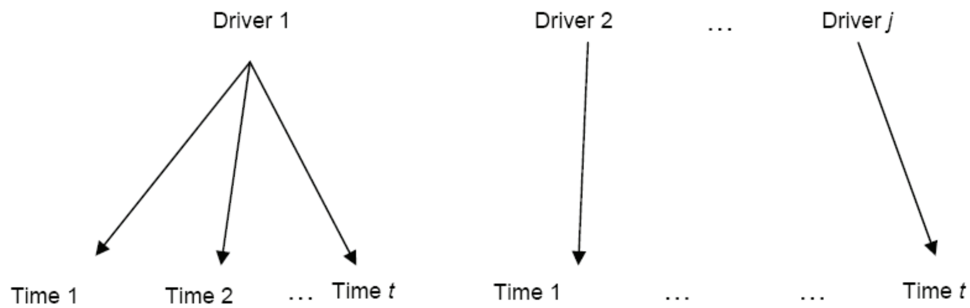

Figure 3. Panel Data Illustration

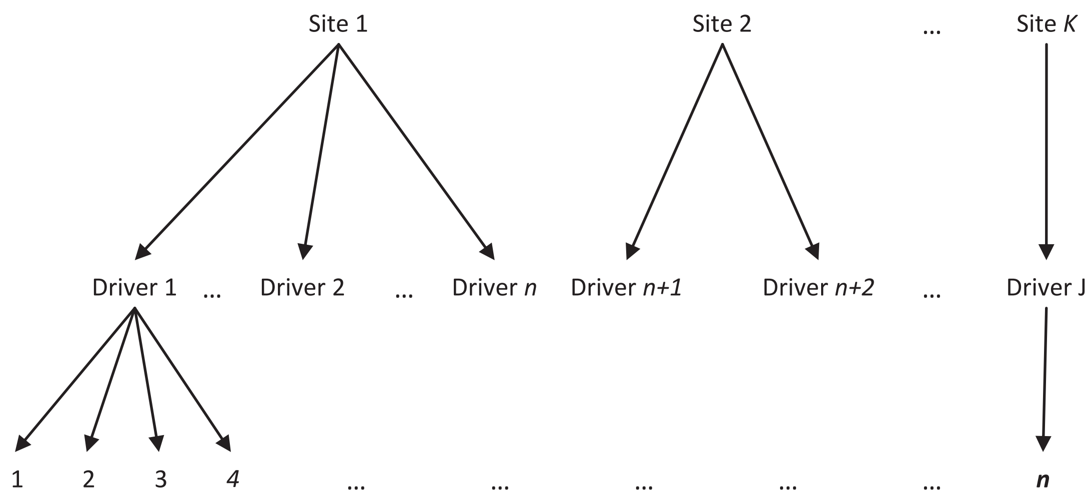

Figure 4. Three-level Data Hierarchy

Park and Saccomanno (2006) estimated models of the 85th-percentile speed reduction between the approach tangent and a horizontal curve. The authors considered both aggregate and disaggregate measures of speed, and single- and multi-level modeling approaches. The authors concluded that disaggregate speeds eliminate the ecological fallacy associated with speed aggregation, and that hierarchical models are able to offer additional insights regarding the association between driver/vehicle, geometric design features, and speed than conventional single-level models such as OLS linear regression. In the multi-level model, the authors found that decreasing the radius of curve is associated with a greater speed reduction between the tangent and horizontal curve. Both the parameter estimate and the standard error of the radius (only independent variable in models) were higher in the multi-level level than in the single-level model, suggesting that the OLS estimator underestimates both as a result of not explicitly accounting for the clustered nature of the data-generating process.

2.3 Operating Speed Models for Low-speed Urban Streets

There is also a considerable amount of published operating speed literature for low-speed urban and suburban streets. Again, the statistical models estimated in these studies are primarily used as design consistency tools, but the relationships between speed and roadway features on these roadway types may provide useful insights regarding transition zone speeds, particularly along the low-speed section. The following relationships between vehicle operating speeds and roadway design features were found for low-speed urban and suburban streets:

- Increasing the degree of curve is associated with a decrease in 85th-percentile vehicle operating speeds (Tarris et al., 1996; Poe and Mason, 2000).
- Increasing the roadside hazard rating from one with a wide clear zone free of fixed objects to one with roadside obstacles closer to the traveled way has been shown to decrease vehicle operating speeds

TABLE 1. Description of Study Sites

Site ID	County	Route and Direction	Segment(s)	Speed Limit Reduction (mph)	Transition Zone Length (ft)
1	Indiana	553WB	0160-0170	55 → 35	535
2	Indiana	56WB	0420	55 → 35	690
3	Jefferson	322 WB	0020-0030	55 → 35	725
4	Juniata	35 NB	0050-0060	55 → 40	540
5	Juniata	35 SB	0070-0080	55 → 40	375
6	Clearfield	453 NB	0390-0410	45 → 25	750
7	Clearfield	879 EB	0100-0110	45 → 25	500
8	Indiana	110 EB	0070-0080	55 → 35	1065
9	Huntingdon	655 SB	0540-0550	55 → 35	750
10	Butler	356 NB	0110	55 → 40	690
11	Indiana	3035 NB	0010-0030	55 → 35	1020
12	Centre	192 EB	0210-0220	55 → 40	800
13	Juniata	35 NB	0510-0520	45 → 25	570
14	Huntingdon	522 NB	0210	40 → 25	925
15	Clearfield	53 NB	0480-0490	45 → 25	460
16	Huntingdon	522 SB	0310-0320	55 → 35	700
17	Huntingdon	45WB	0080-0090	55 → 35	675
18	Centre	3040 NB	0360-0370	45 → 35	665
19	Huntingdon	550SB	0110-0120	55 → 35	410
20	Centre	550 NB	0520-0540	55 → 40	860

Note: NB = Northbound; SB = Southbound; EB = Eastbound; WB = Westbound

on low-speed urban streets (Poe and Mason, 2000; Wang et al., 2006).

- Fitzpatrick et al. (2001) found that increasing the lane width and the presence of a raised median or two-way left-turn lane are associated with significant vehicle speed increases at the mid-point of horizontal curves on low-speed urban and suburban arterials.
- Wang et al. (2006) found that the presence of a sidewalk, the presence of on-street parking, and the presence of t-intersections all decrease vehicle operating speeds at the mid-point of horizontal curves on low-speed urban streets. The authors found that the presence of curb and gutter on low-speed urban streets is associated with vehicle speed increases.

From a methodological perspective, panel (Tarris et al. 1996) and mixed models (Poe and Mason 2000; Wang et al. 2006) have been used to estimate models of vehicle operating speeds on low-speed urban streets. Panel data are useful when individual vehicle speeds are “tracked” along a roadway section, which was the case in the study by Tarris et al. (1996), where vehicle speeds were recorded on the approach tangent and at three locations along a horizontal curve. Driver or vehicle effects, and time effects, are both considered in this framework. Mixed models include both fixed (e.g., geometric elements along roadway) and random (e.g., data collection sites) effects in the modeling framework.

2.4 Summary

The main findings from the operating speed model literature are that a variety of geometric and roadside design features influence vehicle operating speeds on rural two-lane highways and low-speed urban streets. There appears to be consensus that sharper curve radii reduce vehicle operating speeds in both environments. Increased available sight distance and increased lane widths also appear to be associated with higher vehicle operating speeds. Steeper vertical grades and greater access density appear to be associated with lower vehicle operating speeds. Reducing the posted speed limit has been shown to reduce vehicle operating speeds, while more hazardous roadside areas have been associated with lower vehicle operating speeds. From a modeling perspective, most past research has estimated vehicle operating speeds using OLS linear regression. In many cases, the 85th-percentile speed was estimated at a point location and this measure was used as the dependent variable in model estimation. More

TABLE 2. Mean and Standard Deviation of Speeds at Study Sites

Site ID	Sample Size	Mean Speed and Standard Deviation of Speed per Sensor (mph)			
		1	2	3	4
1	124	47.9 (7.24)	49.6 (7.20)	50.3 (6.07)	47.6 (7.12)
2	68	52.8 (9.50)	52.4 (7.71)	44.2 (8.47)	43.1 (8.04)
3	98	51.3 (5.44)	49.9 (5.72)	46.3 (6.17)	43.1 (6.15)
4	104	57.6 (7.97)	53.9 (7.69)	52.6 (6.67)	48.2 (6.75)
5	231	58.2 (6.78)	52.3 (7.16)	49.6 (6.79)	45.5 (6.81)
6	99	42.6 (7.18)	41.6 (6.00)	35.8 (7.37)	28.7 (6.26)
7	159	52.0 (6.11)	47.0 (5.62)	44.4 (6.91)	37.4 (6.19)
8	149	57.1 (6.20)	53.0 (7.02)	49.5 (7.50)	46.7 (6.48)
9	478	58.4 (6.40)	53.1 (5.92)	48.3 (7.02)	47.4 (7.65)
10	148	51.7 (6.08)	51.0 (5.82)	49.6 (5.90)	49.0 (6.14)
11	141	43.3 (6.88)	41.4 (6.11)	36.6 (5.30)	36.9 (5.96)
12	73	54.5 (6.20)	52.6 (5.96)	48.8 (7.09)	38.9 (9.57)
13	130	43.8 (6.89)	41.7 (5.02)	28.4 (4.08)	30.1 (4.42)
14	112	53.4 (7.03)	49.2 (6.17)	39.2 (5.81)	36.1 (5.97)
15	81	46.7 (5.98)	41.7 (5.02)	41.7 (5.42)	36.6 (5.89)
16	122	54.0 (6.90)	50.8 (5.51)	45.7 (6.20)	36.7 (5.66)
17	164	58.2 (6.25)	55.5 (6.08)	50.4 (6.04)	46.3 (6.02)
18	52	58.1 (7.54)	53.3 (7.06)	52.0 (6.31)	50.8 (6.08)
19	178	50.2 (5.75)	45.5 (5.31)	49.5 (6.44)	42.5 (6.01)
20	148	53.3 (5.56)	52.0 (6.01)	47.8 (5.58)	43.9 (6.26)
Total:	2,859 drivers	11,436 speed observations			

recently, however, several authors have recommended the use of disaggregate data and thus employed panel (Tarris et al. 1996; Figueroa and Tarko 2005), mixed (Poe and Mason 2000), or multi-level modeling (Park and Saccomanno 2006) approaches.

3. SPEED OBSERVATION METHODS

Study sites in central Pennsylvania were examined and road features and operating speed data were collected at several two-lane rural highway transition zones to identify which highway characteristics are associated with passenger car operating speeds. This section describes the site selection process and the data collected at the selected study sites.

3.1 Site Selection

Potential study sites were initially identified by reviewing the Pennsylvania Department of Transportation (PennDOT) online video photolog system. Only study sites along two-lane rural highway sections in which the posted speed limit was reduced by at least 15 mph, as indicated by regulatory signs, were considered. An essential requirement of the study sites was the presence of both a Reduced Speed Ahead sign followed by a Speed Limit sign indicating a lower posted speed limit. The location of these two signs marked the limits of the transition zone. Figure 1 is an example of a two-lane rural highway transition zone where the posted speed limit changes from 55 to 40 mph.

Following initial site identification, field visits confirmed if the locations met speed reduction requirement, as well as the following criteria:

1. Free of signalized or stop-controlled intersections along the major road within 2 miles of the limits of the transition zone, so that traffic flow is not influenced by an external cause.
2. Less than 10 percent heavy vehicles to limit the influence of trucks and other heavy vehicles on passenger car driver speed choice.
3. Low-volume highways in order to maximize the probability of collecting free-flow vehicles. Past research has identified low-volume highways as those with an average daily traffic (ADT) volume less than 4,000 vehicles per day (McFadden and Elefteriadou, 2000).
4. Smooth pavement surfaces and visible pavement markings.

TABLE 3. Summary Statistics of Highway Features

Continuous Variable	Mean	St Dev	Minimum	Maximum
Transition Zone Length (ft)	685.3	189.5	375	1065
Lane Width (ft)	10.65	0.570	9.7	13
Paved Shoulder Width (ft)	3.43	1.911	0	8.6
Stabilized Shoulder Width (ft)	1.27	1.807	0	12
Paved Roadway Width (ft)	28.33	4.493	23	41
Lateral Clearance (ft)	8.88	5.244	0	30
Grade (%)	-0.50	2.926	-9.2	5.6
Total No. of Driveways (both sides of road)	2.02	1.787	0	7
Categorical Variables	**Proportion in Sample (%)**			
Posted Speed Limit = 25 mph	10.2			
Posted Speed Limit = 35 mph	27.5			
Posted Speed Limit = 40 mph	14.3			
Posted Speed Limit = 45 mph	9.1			
Posted Speed Limit = 55 mph	38.9			
Presence of Horizontal Curve with a Warning Sign	20.2			
Presence of Horizontal Curve without Warning Sign	29.2			
Presence of Curb	17.9			
Presence of Guardrail	21.7			
Presence of Intersection Warning Sign	9.3			
Presence of School or Children Warning Sign	10.2			
Presence of a Curve Ahead Warning Sign	11.4			

By selecting sites with these characteristics, the probability that driver behavior would be influenced by factors other than the existing highway features was minimized. Twenty sites in central Pennsylvania that met these criteria were selected for speed observation. Table 1 summarizes the location of each site as well as the changes in speed limit and the length of each transition zone.

3.2 Site and Speed Data Collection

At each study site, speed, roadway, roadside, traffic control, and land use data were collected. Speed data were collected using Nu-metrics Hi-Star sensors, which use vehicle magnetic imaging technology to record time stamp, point speed, vehicle length, and pavement temperature and condition (dry or wet) data. The sensors are 6.5 inches by 5.5 inches, with a profile of 0.625 inches, and are placed in the center of the travel lane. A rubber cover was used to protect them and to reduce their conspicuity, thus reducing the likelihood that drivers adjust their speeds due to visible equipment and data collection personnel.

At each study site, a total of four sensors were placed as shown in Figure 2. Sensors #2 and #3 were placed adjacent to the Reduced Speed Ahead sign and the regulatory Speed Limit sign, respectively. These locations defined the limits of the transition zone. Two additional sensors were placed 500 feet before and after the limits of the transition zone. The purpose of these additional sensors was to collect speed data beyond the limits of the transition zone to determine if driver speed choice changed prior to entering or after passing through the transition zone.

Speed data were collected during daylight hours, under favorable weather conditions. Only data from vehicles with time headways of at least 5 seconds were included in the database as these have been previously identified as free-flow vehicles (McFadden and Elefteriadou, 2000). Free-flow vehicles were selected so that speed choice was only influenced by the features present along the transition zone. The layout of the sensors permitted a vehicle at a site to be "tracked," thus only vehicles in which speed information was collected at all four sensor locations were included in the analysis database. Speeds from 2,859 free-flow passenger vehicles were collected during the study period. A total of 11,436 individual vehicle point speeds were included in the sample. Descriptive speed statistics for all measurements locations at each study site are shown in Table 2.

As noted previously, information on the speed limit change and the length of the transition zone at each study site were recorded. In addition, other highway features that were expected to influence driver behavior, such as traffic control

TABLE 4. Fixed-Effects Panel Data and Three-level Models

Parameter	Fixed-effects Panel Data			Three-Level Model		
	Est.	SE	t	Est.	SE	Z
Speed Limit 25 mph (1: posted speed limit at point location is 25 mph; 0: otherwise)[a]	-10.46	0.537	-19.49	-10.54	0.524	-20.11
Speed Limit 35/40 mph (1: posted speed limit at point location is 35 or 40 mph; 0: otherwise)[a]	-2.20	0.173	-12.71	-2.21	0.173	-12.77
Speed Limit 45 mph (1: posted speed limit at point location is 45 mph; 0: otherwise)[a]	-3.41	0.481	-7.09	-3.48	0.469	-7.42
Lane width (ft)[b]	3.49	0.354	9.85	3.34	0.342	9.78
Lateral Clearance (ft)	0.16	0.011	15.33	0.16	0.011	15.26
Total Number of Driveways (both sides)	-0.95	0.034	-27.69	-0.95	0.034	-27.78
Curb Indicator (1: curb present; 0: no curb present)	-4.01	0.235	-17.09	-4.00	0.233	-17.14
Intersection WS (1: intersection warning sign present; 0: otherwise)[c]	-1.91	0.228	-8.36	-1.93	0.227	-8.50
School/Children WS (1: school or children warning sign present; 0: otherwise)[c]	-1.08	0.199	-5.43	-1.09	0.199	-5.47
Curve Ahead WS (1: curve ahead warning sign present; 0: otherwise)[c]	0.84	0.186	4.51	0.85	0.186	4.59
Curve with WS (1: presence of a horizontal curve with a warning sign; 0: otherwise)[d]	-3.46	0.197	-17.51	-3.42	0.197	-17.42
Curve without WS (1: presence of a horizontal curve without a warning sign; 0: otherwise)[d]	-1.68	0.164	-10.25	-1.67	0.163	-10.22
Constant	47.05	0.604	77.95	46.70	0.976	47.86
Standard Deviations -Random Components	**Fixed-effects Panel Data**			**Three-Level Model**		
Site	N/A			3.432		
Driver	6.202			4.457		
Residual	5.007			5.004		
Goodness-of-fit Measures	R^2 = 47.2% (within) R^2 = 22.2% (between) R^2 = 32.7% (total)			Log-likelihood = -36,723.8		

[a]The baseline is 55 mph and was set equal to zero.

[b]The lane width variable indicates the travel lane width beyond 9 feet. For example, if the lane width at a point location was measured as 10 feet, the input for the lane width variable in the model would be 1 foot.

[c]The baseline is no warning sign or the presence of a warning sign that does not indicate a change in highway alignment, a change in access density, or presence of children, and was set equal to zero.

[d]The baseline is a tangent roadway section and was set equal to zero.

devices, access density, horizontal and vertical alignment data, cross-section dimensions, and land use characteristics were collected in the region adjacent to each speed sensor. Descriptive statistics for all data collected at each study site are shown in Table 3.

4. METHODOLOGY

As noted in the literature review, the most common method to estimate vehicle operating speeds is OLS linear regression. However, since speed data were collected at four point locations along transition zones, the speed at a certain sensor is related to the speed at previous sensors for a specific driver, thus the assumption of independent observations associated with the OLS estimator is violated. In order to identify the factors that are associated with driver speed choice in transition zones, panel data and multilevel models were used in the present study.

4.1 Panel Data Model

Panel data are a form of longitudinal data in which observations in a sample are collected at two or more points in time. The sample is viewed as a cross-section of drivers where the speed observations are repeated measurements on each driver over time. In this study, driver speeds were observed sequentially at four sensor locations, each representing a point in time. The structure of the data can be represented by clusters of drivers, each cluster having four speed observations. This is shown in Figure 3.

As shown in Figure 3, information on each driver j is collected at several time periods t. In the present study, $t = 1, \ldots, T$, where $T = 4$, corresponding to the four sensor locations. When there are no missing observations, the panel is balanced. There are several advantages to using a panel data model as opposed to an OLS linear regression model when speed observations are clustered within drivers, including (Brüderl, 2005):

1. There is more variability, less collinearity, and more degrees of freedom, thus panel data is considered more informative than other methods when data contain both cross-section and time dimensions;
2. The panel data estimates are more efficient than those produced by the OLS estimator;
3. Panel data permits the study of individual driver dynamics by considering unit-specific clusters (i.e., individual drivers);
4. The time-ordering of individual speed observations are explicitly considered; and,
5. Individual unobserved heterogeneity (i.e., variation of observations due to variables not included in the model) is accounted for in a panel data model.

The basic form of a panel data model is shown in Equation (1) below (Baltagi, 2008):

$$y_{jt} = \alpha + \beta X'_{jt} + u_{jt} \tag{1}$$

where:

y_{jt} = speed of driver j at time t, $j = 1, 2, \ldots, n$; $t = 1, 2, \ldots, T$;

α = scalar;

β = vector of estimable parameters;

X'_{jt} = vector of explanatory variables corresponding driver j at time t; and

u_{jt} = disturbance term corresponding to driver j at time t.

In a one-way error components model, the disturbance takes the following form:

$$u_{jt} = \mu_j + v_{jt} \tag{2}$$

where: μ_j = unobservable driver-specific effect; and

v_{jt} = remaining disturbance for driver j at time t.

Panel data can be estimated using either the fixed or random effects models. The μ_j in equation (2) is both fixed and estimable, while the remaining disturbance (v_{jt}) is stochastic and independent and identically distributed in the fixed effects model. The explanatory variables (X_{jt}) are assumed independent of the remaining disturbance (v_{jt}) for all drivers j at time t. An F-test can be used to test the hypothesis that the individual driver-specific effects (μ_j) are equal. The fixed effects model has several limitations – the parameter estimates (β) are conditioned on the drivers included in the sample, the time-invariant explanatory variables will be perfectly collinear with the driver-specific effect (μ_j), and a considerable loss of degrees of freedom is associated with allowing each individual driver to have a different intercept (Kennedy, 2003). The OLS estimator is used to estimate fixed effects models.

In a random effects model, driver-specific effects (μ_j) can be assumed random; however, μ_j and v_{jt} are both assumed independent and identically distributed, and the μ_j and v_{jt} are assumed independent of one another (Baltagi, 2008). As a result, the explanatory variables (X_{jt}) are assumed independent of the driver-specific random effect (μ_j) and the remaining disturbance (v_{jt}) for all drivers j at time t. Generalized least squares are used to estimate random effects models.

A Hausman test can be used to test the assumption that there is no correlation between the individual driver effects (μ_j) and the vector of explanatory variables. The null hypothesis is that there is no correlation between the driver-specific effects and the vector of explanatory variables.

4.2 Multilevel Models

Because the data in the present study were collected at 20 different sites, and drivers do not travel through all sites, the study site introduces another possible hierarchy in the data structure. This is illustrated in Figure 4. Here, speed observations are nested within drivers, which are then nested within the study sites.

Multilevel models are able to account for correlated observations and a clustered, hierarchical data structure. Such models are formally represented by different submodels; the submodels estimate statistical associations at a given level, including how these relationships influence associations at another level. The panel data models described previously accommodated two-level data structures; however, multilevel models are estimated in the present study to account for the three-level hierarchy of the data. To introduce the concept of a three-level hierarchical linear model, first consider a fully unconditional model. In this model, no explanatory variables are included in the model specification at any level, so that the variation in an outcome (operating speed) can be assessed at all levels in the data hierarchy. In the context of the present study, point speeds are nested within drivers, and drivers are then nested within data collection sites (see Figure 4). At the lowest level of the data hierarchy, the expected operating speed at point location i is modeled as a function of the driver mean plus a random error term, as shown in Equation (3) [Raudenbush and Bryk, 2002]:

$$Y_{ijk} = \pi_{0jk} + e_{ijk} \tag{3}$$

where:

Y_{ijk} = operating speed at point location i for driver j and data collection site k;
π_{0jk} = mean operating speed for driver j at data collection site k;
e_{ijk} = random point speed effect, assumed N~$(0, \sigma^2)$.

The indices i, j, and k denote point speeds, drivers, and data collection sites, respectively, where $i = 1, 2, \ldots, n_{jk}$, $j = 1, 2, \ldots, J_k$, and $k = 1, 2, \ldots, K$.

At the second level of the data hierarchy, the driver mean speed is modeled as a function of the data collection site mean and a random error term as shown in Equation (4):

$$\pi_{0jk} = \beta_{00k} + r_{0jk} \tag{4}$$

where:

β_{00k} = mean operating speed at data collection site k;
r_{0jk} = random driver speed effect, assumed N~$(0, \tau_\pi)$.

At the highest level of the data hierarchy shown in Figure 4, the variability among the data collection sites is specified as a function of the grand mean plus a random error term, as shown in Equation (5):

$$\beta_{00k} = \gamma_{000} + u_{00k} \tag{5}$$

where: γ_{000} = grand mean;
u_{00k} = random data collection site effect, assumed N~$(0, \tau_\beta)$.

Substituting Equation (5) into Equation (4) yields the following:

$$\pi_{0jk} = \gamma_{000} + u_{00k} + r_{0jk} \tag{6}$$

Substituting Equation (6) into Equation (3) yields a fully unconditional model, where the variance in point speeds (Y_{ijk}) is decomposed into three components corresponding to the three-level data hierarchy shown in Figure 4, as follows (Steenbergen and Jones, 2002):

$$Y_{ijk} = \gamma_{000} + u_{00k} + r_{0jk} + e_{ijk} \tag{7}$$

By partitioning each level of the data hierarchy into its three components, the total variability in the operating speed (Y_{ijk}) can be determined as follows (Raudenbush and Bryk, 2002):

$$\frac{\sigma^2}{\sigma^2 + \tau_\pi + \tau_\beta} \tag{8}$$

$$\frac{\tau_\pi}{\sigma^2 + \tau_\pi + \tau_\beta} \tag{9}$$

$$\frac{\tau_\beta}{\sigma^2 + \tau_\pi + \tau_\beta} \tag{10}$$

Equation (8) represents the proportion of variance within drivers; equation (9) is the proportion of variance among drivers within data collection sites; and, equation (10) is the proportion of variance among data collection sites.

A fully unconditional model is first estimated to evaluate the variance components (e_{ijk}, r_{0jk}, and u_{00k}), using restricted maximum likelihood. A likelihood ratio test is used to test the null hypothesis of no variability among point speeds, drivers, and data collection sites, respectively.

In a conditional model, explanatory variables may be included at any (or all) levels of the model to explain the variability associated with each level. In the context of the present study, the roadway, roadside, traffic control, and land use variables were measured at each data collection point, thus were included as explanatory variables in the point-speed level 1 model. To do so, the following term was added to Equation (3): $\sum_{p=1}^{P} \pi_{pjk} a_{pijk}$, where $p = 1, \ldots, P$ roadway, roadside, traffic control, and land use variables and a_{pijk} represents the estimable regression parameters. Data related to drivers and the overall data collection sites were not measured, thus, explanatory variables were not included in the model as levels 2 and 3. Levels 2 and 3 were estimated using Equations (4) and (5). The resulting conditional model estimated in the present study is shown below in Equation (11):

$$Y_{ijk} = y_{000} + \sum_{p=1}^{P} \pi_{pjk} a_{pijk} + u_{00k} + r_{0jk} + e_{ijk} \tag{11}$$

All terms in Equation (11) are as previously defined. The model was estimated using restricted maximum likelihood, which offers advantages over alternative approaches (e.g., maximum likelihood) when the number of level 1 or level 2 units are unbalanced within level 2 or level 3 units, respectively, or when the sample size is small at any level (Raudenbush and Bryk, 2002).

5. RESULTS

5.1 Panel Data Analysis

Since four speed observations, corresponding to the four sensor locations, were identified for each driver included in the database, the variable "driver" was set as the panel variable while the "sensor" variable was set as the time variable in the panel data analysis. Both fixed-effects and random-effects models were estimated. The Hausman test rejected the null hypothesis that the random-effects estimator is consistent ($\chi2$ [12 df] =10,211.31, p-value < 0.0001), thus favoring the fixed-effects model. The estimated fixed effects panel model is shown in Table 4.

All of the parameter estimates for the fixed-effects panel data model have t-statistics greater than 1.96 ($p < 0.05$), indicating that each explanatory variable is statistically significant at the 95-percent confidence level. All signs for the parameter estimates are of plausible sign.

When compared to the baseline posted speed limit of 55 mph, all of the posted speed limit indicators in Table 4 are negative. This indicates that posted speed limits less than 55 mph are associated with lower expected operating speeds in two-lane rural highway transition zones, holding all other variables constant. This finding was expected; however, the magnitude of the indicators is noteworthy. In the present sample, all 14 of the study sites with a 55 mph posted speed limit in advance of the transition zone had either 35 or 40 mph posted speed limits at the low-speed end of the transition. The 35/40 mph indicator (-2.20 mph), relative to the baseline of 55 mph indicates that drivers do not reduce their operating speed to a level commensurate with the posted speed limit change (15 or 20 mph).

The 45 mph indicator is representative of the high-speed end of five transition zone locations. The parameter estimate (-3.41 mph) for this variable suggests that drivers select operating speeds that are not considerably lower than travel speeds at a transition zone site with a 55 mph posted speed limit, holding all other variables constant. There were four transition zones sites with a 45 to 25 mph posted speed limit reduction. The difference in the magnitude of these indicator variables is 7.01 mph (-10.46 – [-3.41]), suggesting that, while drivers do not select operating speeds commensurate with the posted speed limit reduction, the mean operating speed reduction is greater than the expected speed reduction in the 55 to 35/40 mph transition zones.

The lane width variable indicates that for each one-foot increase in lane width beyond 9 feet, a 3.5 mph increase in vehicle operating speed is expected. This finding was expected since wider lanes increase driver comfort, resulting in higher expected operating speeds.

For each unit increase (one foot) in the lateral clearance along the roadway, the expected vehicle operating speed is expected to increase by 0.16 mph. This finding was expected as a roadside clear of fixed objects, steep slopes, and other hazards provides a greater level of driver comfort and is thus associated with an increase in vehicle speed.

A one unit increase in the total number of driveways along the transition zone is associated with a 0.95 mph decrease in the expected operating speed. This finding was expected because increasing the number of driveways increases the number of conflict points along a roadway segment.

The indicator variables for the presence of curb, intersection warning sign, school or children warning sign, and the presence of a horizontal curve with or without an advance warning sign are all negative. The presence of a curb is associated with a 4 mph decrease in the expected operating speed along a transition zone, when compared to the baseline of no curb. This finding was expected as the presence of curb and gutter typically communicates to the driver that they are entering a low-speed zone, and because the presence of curb reduces the available clear zone. As a result, drivers were expected to reduce their operating speed.

The presence of an intersection warning sign is associated with a mean speed reduction of 1.9 mph when compared to the baseline. The baseline in this case is no warning sign or the presence of a warning sign that does not indicate a change in highway alignment, a change in access density, or presence of children. The presence of a warning sign related to the presence of a school or children is associated with a mean speed reduction of 1 mph when compared to the baseline of no warning sign or the presence of a warning sign that does not indicate a change in highway alignment, a change in access density, or presence of children.

The horizontal curve presence indicators, one with an advanced warning sign and one without an advanced curve warning sign, are associated with an expected speed reduction of 3.4 and 1.7 mph, respectively, when compared to the baseline condition. In this case, the baseline condition was a tangent roadway section along the two-lane rural highway transition zone. This finding was expected because horizontal curvature has been shown to reduce vehicle operating speeds in past design consistency research as noted in the literature review.

The curve ahead warning sign indicator in Table 4 was positive. This indicates that the presence of a curve ahead warning sign was associated with an expected increase in vehicle operating speeds when compared to the baseline of no warning sign or presence of a warning sign that does not indicate a change in highway alignment, a change in access density, or indicates presence of children. While this finding may be perceived as counterintuitive, it is likely an artifact of the speed variance present at observation locations with a curve ahead warning sign. In the present study, the standard deviation of speeds at locations with a curve ahead warning sign was 11.18 mph. For the baseline condition, the standard deviation of speeds was 8.48 mph. As such, the speed variance is significantly greater at locations with a curve ahead warning sign than at other locations without warning signs.

The panel data model estimation results indicate that a standard deviation of 6.2 mph is associated with different drivers while a standard deviation of 5 mph is associated with the presence of the driver cluster. The overall coefficient of determination for the fixed effects panel model was 0.327, indicating that the model explains 33 percent of the overall variance in speed observations. The values for the within- and between-drivers coefficients of determination were 0.472 and 0.222, respectively, indicating that the model estimated explains 47 percent of the variance associated with the driver cluster while explaining 22 percent of the variance associated with different drivers (from driver to driver). The F-statistic for the hypothesis that the individual driver-specific effects (μ_j) are equal was rejected ($F = 5.65$, $p < 0.05$), thus indicating that there are differences between individuals (drivers j) and there is individual-specific heterogeneity. This finding suggests that accounting for the clustered nature of the data is able to capture some of the variance associated with individual drivers, which is not possible in a single-level modeling framework often used in past operating speed modeling research (i.e., OLS linear regression).

5.2 THREE-LEVEL HIERARCHICAL LINEAR MODEL

A second model was estimated using a multilevel modeling approach in order to include a "site" variable at the highest level of the data structure. Unconditional models, with and without specifying the level variables were fitted and likelihood-ratio tests were performed between these models.

Two likelihood-ratio tests were performed in order to verify that both "driver" and "site" levels were necessary. The first test compared the models with and without the driver group; the likelihood-ratio test yielded a χ^2 test-statistic of 745.20 (p-value < 0.0001), thus rejecting the null hypothesis that the variance component for drivers is zero. Similarly, a second likelihood-ratio test was performed between the models with and without the group component for sites. The test-statistic χ^2 resulted in a value of 1724.01 (p-value < 0.0001) thus indicating that the group level site variance component was different from zero.

The results of the likelihood-ratio tests indicated that a three-level model in which speed observations are nested in drivers, which are nested in sites, is able to capture the variance components in a three-level hierarchy. As such, the three-level model offers improvements over two-level models, where either speed observations are nested in drivers (site level not included) or where speed observations are nested in sites (driver level not included).

The three-level model estimated in the present study included the same variables found to be statistically significant in the panel data model. The results of the three-level model are also included in Table 4 as a means to compare the estimates between the three-level and the fixed-effects panel data model. Interpretation of the parameter estimates from the multilevel model is nearly identical to the fixed effects panel model and is not repeated here.

When comparing the parameter estimates and standard errors across the fixed effects panel and three-level hierarchical models shown in Table 4, both are similar. The greatest change in the parameter estimates between the two models occurred in the lane width variable, by a magnitude of 0.15 mph (less than 5 percent change). With regards to the standard errors, those in the multilevel model were generally lower, but the relative difference was less than 3 percent.

The standard deviation of the random component for the residual (lowest level) is very similar between the two models (5.007 mph in the panel model and 5.004 mph in the multilevel model). The greatest difference between the two models estimated relates to the driver and data collection site-level variance components. In the panel model, the variance component associated with drivers was 6.202 mph, while it was 4.457 mph in the multilevel model. The multilevel model showed that some of the driver level of variance was attributable to unobserved data collection site characteristics. In the multilevel model, the site-level variance component was 3.432 mph.

6. CONCLUSIONS AND RECOMMENDATIONS

Speed data were collected along 20 rural two-lane high- to low-speed transition zone sites in central Pennsylvania. Roadway, roadside, traffic control, and land use variables were collected at each site to identify the highway variables that were associated with point operating speeds. Since vehicles were tracked along the study sections, and individual driver speed information was obtained, panel data and multilevel model analyses were performed since these models are able to account for correlated observations in a longitudinal modeling framework.

Panel data analysis suggested that a fixed-effects model was favored over the random-effects model as indicated by the results of the Hausman test. The parameter estimates and standard errors resulting from the multilevel model estimated in the present study were nearly identical to those resulting from the estimated panel model. The variables associated with point-level operating speeds along transition zones in the fixed-effects panel data model were posted speed limit, number of driveways, presence of curb, warning signs related to presence of intersection and presence of children and school, and changes in horizontal alignment. The highway characteristics that were associated with higher speeds were wider lane widths, wider lateral clearance distances, and the presence of a Curve Ahead warning sign. With regards to designing transition zones on two-lane rural highways, it appears that narrowing the cross-section in the segment between the high- and low-speed zones may offer speed reduction benefits. In addition, the presence of a curb in the low-speed zone may provide some indications that lower vehicle operating speeds are desirable.

Although the panel model was able to accommodate clustered data in a two-level hierarchy, the multilevel model was able to accommodate the three-level hierarchy of the data collected in the present study. While the three-level model showed the existence of site-level variance, much of the variance at the site-level was likely captured by the driver variance in the panel model. Future research should consider collecting and incorporating driver- and site-level explanatory variables in a three-level hierarchical model to learn more about how these variables effect the level 2 and level 3 variance components.

There are several advantages to estimating vehicle operating speeds using panel or multilevel modeling approaches. First, the variability between drivers (individuals) at specific sites can be estimated. Single-level models often require data aggregation at point speed measurement locations and thus enable only the effects of the site characteristics to be included in model estimation. Second, the multilevel model presented in the present study also enables the variance of a longitudinal study to be partitioned into components for drivers and sites.

Although the final dataset for this research consisted of 11,436 speed observations from 2,859 drivers, these data were collected at only 20 sites. In some cases, the variability in the highway site characteristic data were limited, thus future research should include a larger sample of two-lane rural highway transition zones with more variability in the explanatory variables considered in this research, particularly the horizontal alignment, vertical profile, and cross-section elements. This additional site characteristic data may also enable the posted speed limit to be included as a fourth-level in a multilevel modeling framework. In this case, the roadway features could be modeled as both nested and crossed effects. Finally, with regards to the site characteristic data, an indicator variable was used to define the presence of a horizontal curve. It is recommended that future operating speed models include the radius of horizontal curve (or degree of curve) as a continuous explanatory variable rather than an indicator variable for the presence of a horizontal curve.

Another recommendation is that future studies should focus on speed variance rather than point mean speeds and take into consideration that speed differentials are desired along transition zones. Design consistency is usually measured in terms of speed differentials; small speed differentials are associated with a good and consistent design (Glennon and Harwood, 1978; McLean, 1979; McFadden and Elefteriadou, 2000; and Fitzpatrick and Carlson, 2002). Studies that aim to develop design guidelines for transition zones should identify threshold limits for speed differentials that are associated with safe speed reductions along these highway sections.

REFERENCES

Baltagi, B. H. (2008). *Econometric Analysis of Panel Data, Fourth Edition,* John Wiley and Sons, Chichester, West Sussex, UK, 35-41.

Brüderl, J. (2005). *Panel Data Analysis,* Manheim; Baden-Württemberg: University of Manheim.

Cruzado, I. and Donnell, E. T. (2010). "Factors Affecting Driver Speed Choice along Two-Lane Rural Highway Transition Zones." *Journal of Transportation Engineering*, 136 (8), 755-764.

Donnell, E. T. and Cruzado, I. (2008). *Effectiveness of Speed Minders in Reducing Driving Speeds on Rural Highways in Pennsylvania*, Final Report prepared for the Pennsylvania Department of Transportation.

Figueroa, A.M. and Tarko, A.P. (2005). "Speed Factors on Two-Lane Rural Highways in Free-Flow Conditions. " *Proc., the 84th Annual Meeting of the Transportation Research Board*, January 2005, Washington, D.C.

Fitzpatrick, K., Elefteriadou, L., Harwood, D. W., Collins, J. M., McFadden, J., Anderson, I. B., Krammes, R. A., Irizarry, N., Parma, K. D., Bauer, K. M., and Passetti, K. (2000). Speed Prediction for Two-Lane Rural Highways, Report No. FHWA-RD-99-171, Federal Highway Administration, McLean, VA.

Fitzpatrick, K., Carlson, P., Brewer, M., and Wooldridge M. (2001). "Design Factors that Affect Driver Speed on Suburban Streets." *Transportation Research Record*. 1751, 18-25.

Fitzpatrick, K., and Carlson, P. (2002). "Selection of Design Speed Values." *Transportation Research Record*. 1796, 3-11.

Glennon, J. C. and Harwood, D. W. (1978). "Highway Design Consistency and Systematic Design Related to Highway Safety." *Transportation Research Record*. 681, 77-88.

Glennon, J.C., Neuman, T.R., and Leisch, J.E. (1985). Safety and Operational Considerations for Design of Rural Highway Curves, Report No. FHWA/RD-86/035, Federal Highway Administration, McLean, VA.

Kennedy, P. (2003). *A Guide to Econometrics, Fifth Edition*, Blackwell Publishers, Malden, MA, USA, 301-318.

Krammes, R., Brackett, R.O., Shafer, M., Ottesen, J., Anderson, I., Fink, K., Collins, K., Pendleton, O., and Messer, C. (1995). *Horizontal Alignment Consistency for Rural Two-Lane Highways*, Report No. FHWA-RD-94-034, Federal Highway Administration, Washington D.C.

Lamm, R. and Choueiri, E.M. (1987). "Recommendations for Evaluating Horizontal Design Consistency Based on Investigations in the State of New York." *Transportation Research Record*. 1122, 68-78.

McFadden, J. and Elefteriadou, L. (2000). "Evaluating Horizontal Alignment Design Consistency of Two-Lane Rural highways." *Transportation Research Record*. 1737, 9-17.

McLean, J. (1979). "An Alternative to the Design Speed Concept for Low Speed Alignment Design." *Transportation Research Record*. 702, 55–63.

Misaghi, P., and Hassan, Y. (2005). "Modeling Operating Speed and Speed Differential on Two-Lane Rural Roads." Journal of Transportation Engineering, 131(6), 408-418.

Park, Y-J., and Saccomanno, F. (2006). "Evaluating Speed Consistency Between Successive Elements of a Two-Lane Rural Highway." *Transportation Research. Part A*, 40(5), 375-385.

Passetti, K. A., and Pambro, D. B. (1999). "Operating Speeds on Curves with and without Spiral Transitions." *Transportation Research Record*. 1658, 9-16.

Poe, C. M., and Mason, J. M. (2000). "Analyzing Influence of Geometric Design on Operating Speeds Along Low-Speed Urban Streets." *Transportation Research Record*. 1737, 18-25.

Raudenbush, S. W. and Bryk, A. S. (2002). *Hierarchical Linear Models: Applications and Data Analysis Methods, Second Edition*, Sage Publications, Inc, Thousand Oaks, CA, USA, 16-67.

Stamatiadis, N., Pigman, J. G., and Hartman, D. (2004). *Safety Consequences of Flexibility in Highway Design for Rural Communities,* Final Report for National Cooperative Highway Research Program Project 15-22.

Stamatiadis, N., Pigman, J. G., and Hartman, D. (2006). "Safety Consequences from Design Flexibility in Rural to Urban Transitions." *Proc., the 85th Annual Meeting of the Transportation Research Board*, January 2006, Washington D.C.

Steenbergen, M. R. and Jones, B. S. (2002). "Modeling Multilevel Data Structures." *American Journal of Political Science*, Vol. 46(1), 218-237.

Tarris, J., Poe, C., Mason, J. M., and Goulias, K. (1996). "Predicting Operating Speeds on Low-Speed Urban Streets: Regression and Panel Analysis Approaches." *Transportation Research Record*. 1523, 46-54.

Wang, J., K. K. Dixon, H. Li, and Hunter M. (2006). "Operating-Speed Model for Low-Speed Urban Tangent Streets Based on In-Vehicle Global Positioning System Data." *Transportation Research Record*. 1961, 24-33.