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Relationships between road design, driver behavior, and crashes in four-lane highways

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Abstract
Safety is typically linked to the road geometry and speed, and speed is directly associated to the road characteristics through the risk perceived by drivers. This endogeneous relationship is not reflected in the current approach of estimating speed and safety effects using single-equation models. This paper presents the results of a study that evaluated road design characteristics, free-flow speeds, crashes, and risk perception of drivers in four-lane highway segments located in suburban and rural areas. The results from single-equation speed and crash models were compared to speed and crash models developed simultaneously. The system of equations includes the effect of speed in the safety model while the effect of crash rate is included in the speed model. The road characteristics are considered exogenous variables in the system. The use of the simultaneous equations approach to calibrate the proposed system of relationships, aside from being the correct formulation to model the endogenous relationship between speed and crashes, improved the identification of speed and crash rate factors when compared with the single-equation modeling approaches.

Keywords
Crash and Speed Factors, Safety Modeling, Simultaneous Equations, Four-lane Highways.

1. Introduction

The investigation of highway crash occurrence and its causation is a prominent research subject due to its significant impact and cost to society. More than 42,000 people die and close to 6.5 million people are injured every year, on average, as a consequence of a motor vehicle crash in the United States. The cost of highway crashes in the United States was estimated as $231 billion for the year 2000, or about $820 per inhabitant (Blincoe et al., 2002).

Motor vehicle crashes are caused by many and very different contributing factors (e.g., road design, drivers, vehicles, weather, etc.). The relationship between crashes and these contributory factors is extremely complex. Highway design guidelines are based primarily on sound engineering judgment and experience. These guidelines are applied to select reasonable design values for the different geometric elements (e.g., cross-section dimensions, horizontal and vertical alignment, etc.) based on a design speed for the highway project. AASHTO (2001) suggests that the design speed should provide safe and continuous operation and should be economically practical and consistent with the speed drivers are likely to expect under normal conditions on the highway. Several researchers (Lamm et al., 1999; Krammes, 2000; Fitzpatrick et al., 2003) have identified circumstances when the relationship between the design speed and the actual highway operating speed is weak or changes with the magnitude of the design speed resulting in design inconsistency problems and increased crash potential.

A great amount of research has been dedicated to investigate and estimate the impacts of the road design on the speed selected by drivers or the crash frequency and severity. Typically, the estimation of the speed and safety effects has been performed separately by applying single-equation models that ignore the two-way (endogenous) relationship between safety and speed, as introduced by the risk perception of drivers, leading to potential bias in the estimation of the speed-safety relationship

2. Objectives

This paper presents the results of a study that evaluated the relationship between road design characteristics, free-flow speeds, and crashes. Single-equation and simultaneous-equations regression models were developed to identify the operational and safety effects of the observed road design characteristics. The objective of this paper is to discuss these effects and promote the use of the simultaneous equations model as an approach to improve the modeling of highway safety.

3. Scope of Work

The study focus on four-lane highway segments located in rural and suburban areas having no traffic interruptions caused by traffic signals or stop signs. Interstate and local roads were excluded. The relationships between free-flow speeds, crashes, and the road characteristics were investigated by considering segments with different horizontal and vertical alignment characteristics, cross-section dimensions, density of access points and intersections, and other road design elements.

4. Methodology

A summary of the research methodology is presented to help readers understand the results of the regression models. The first step identified data collection candidates from a sample of four-lane highway segments located in suburban and rural areas in Indiana. An effort was made to avoid segments that experience congested conditions or have traffic signals that influence free-flow speeds.

The next step was the collection of road characteristics, free-flow speeds, and crash data on the selected highway segments. The speed and road design data was obtained directly from field measurements. The crash data was obtained from the Indiana State Police Accident Information System database. The data collection process took place from May to October 2003. A large variety of road configurations was observed in terms of cross-section dimensions, roadside clear zones, median types, access densities, and other road geometry features. Table 1 presents a summary of the data collected for 67 four-lane highway segments. The segments are not contiguous and do not systematically share crash rates, traffic volumes, or road characteristics. The average segment length is 1.2 miles (1.93 km).

The third step was the risk perception study of drivers. The study required voluntary licensed drivers to watch a series of four-lane highway segments videotaped from the driver position under free-flow conditions. The results of this study were used to establish the hypothesis that drivers used their own perception of the risk on the highway, based on the observed road characteristics, to adjust their speed.

Table 1: Descriptive Statistics of Selected Road Characteristics

Road design characteristic	Mean value	Standard deviation	Minimum value	Maximum value
Mean speed, mph	53.72	5.30	42.05	62.29
85th percentile speed, mph	58.69	5.29	47.46	67.00
Crashes	69.33	65.59	3	271
Crash rate, crashes per vehicle-mile traveled (VMT x 10^6)	2.55	2.17	0.10	11.39
Posted speed limit, mph	50.22	5.18	40	55
Average annual daily traffic, vpd	21,734	11,614	3,550	58,580
Sight distance, ft	1,424.00	408.70	549.45	2,078.00
Longitudinal grade, percent	0.006	1.42	-6.20	6.00
Intersection density, # per mi	4.60	3.53	0	14
Driveway density, # per mi per direction	8.24	10.09	0	38
Median opening density, # per mi	0.48	1.91	0	10
Traveled way width, ft	23.46	0.88	21.41	25.83
Roadside clear zone, ft	23.27	16.27	0	81.50
Median width, ft	25.60	19.75	0	62.08
Curve radius, ft	2,108.69	764.21	969.71	3,695.59
Superelevation rate, percent	3.22	1.81	1.18	6.65
Curve length, ft	1,578.60	1,723.70	165.00	5,300.00

In the next two research stages, single-equation models for speeds and crashes were developed. The free-flow speed model was calibrated using ordinary least squares (OLS) regression using a panel data and the crash frequency model was calibrated using Negative Binomial (NB) regression. In the final research stage, a model that considers the relationships between road design, driver behavior and crash rates was developed using a system of equations. The system of equations was calibrated by applying three-stage least squares (3SLS) regression and including the endogenous relationship between mean free-flow speed and crash rate. The simultaneous equations were solved into their reduced forms to identify the impact of the road characteristics on the free-flow mean speed and crash rate. The results obtained for the proposed system of relationships were compared against the results from the single-equation crash and speed models to present its advantages and contributions to the field of highway safety modeling.

5. Development of Regression Models

5.1 Risk Perception Study

The risk perception survey evaluated the interaction between the road design and the driver behavior on four-lane highways. Forty-eight segments were recorded for 30 seconds during weekdays, in daylight and good weather conditions, off-peak hours and under very low traffic while traveling in the right lane. Each subject watched eight videos (four segments at two different speeds). Each subject watched one segment from each one of the four levels of crash rates in the sample: the first level includes segments with the lowest crash rates (less than 1 crash per million VMT) and the fourth level includes segments with the highest crash rates (more than 3 crashes per million VMT). Subjects were instructed to provide a safety rating for each segment based only on the observed road characteristics in the video. The scale provided an ordinal ranking from 0 if the segment was perceived as being least safe to 4 if the segment was perceived as being very safe. Additional survey details are presented in Figueroa et al., 2005.

A total of 112 subjects, 59 males and 53 females, participated voluntarily in the risk perception survey. All the subjects were licensed drivers with their ages ranging from 18 to 72 years old. The sample has a large variability in driving experience, from one to 60 years, and driving exposure, as represented by the annual miles traveled. These two variables were identified by Jonah (1986) and Renge (1998) as important factors that affect the risk perception of drivers. More experienced and highly-exposed drivers are more likely to perceive risks and hazards on highways more effectively than novice drivers.

An ordered probit model with random effects was developed to evaluate the individual safety ratings based on the effects of the subjects' demographic characteristics and the road characteristics. The ordered probit model is derived by defining an unobservable variable, y_i^*, that is used as a basis for modeling the ordinal ranking of the data. The unobserved variable is specified as a linear function for each observation. Readers interested in details about the ordered probit model are referred to Washington et al. (2003). The ordered probit model is given by

$$y_i^* = \boldsymbol{\beta}\,\mathbf{X}_i + \varepsilon_i, \quad \varepsilon_i \sim N[0,1], \tag{1}$$

where X is a vector of variables determining the discrete ordering for observation i, β is a vector of estimable parameters, and ε is the random normal disturbance.

The best specification of the ordered probit model is shown in Table 2. Only the results for the significant parameters representing road characteristics are presented. All the parameters in the model are significant with a 90 percent confidence level. The model accurately predicts 43.2 percent of the actual survey outcomes. The parameter sigma is statistically significant in the model, confirming the presence of a random effect because of the same individual assigning various ratings.

The ordered probit model includes five demographic indicator variables and seven road characteristics variables. A positive parameter value in the model indicates that an increase in the value of that parameter unambiguously increases the probability that the highway segment is perceived as being very safe and unambiguously decreases the probability that the highway segment is perceived as being least safe.

5.2 Speed Modeling

The speed modeling task evaluated the interaction between the road design and the free-flow speed of drivers on four-lane highways. The mean free-flow speed and its variability across drivers are considered important safety factors in designing roads and setting speed limits. An increase in mean speed increases the severity of crashes, while an increase in speed variability increases the frequency of interactions between vehicles, which can be associated with an increase in the crash frequency.

Figueroa and Tarko (2004) developed an advanced method of modeling free-flow speeds that is able to estimate any percentile speed and considers the effect of the road characteristics on both the mean speed and the speed dispersion at each highway site. The model represents percentile speeds as a linear combination of the mean and the standard deviation based on the assumption of normally-distributed free-flow speeds at any site. The speed model is given by

$$V_{ip} = m_i + Z_p \cdot \sigma_i + \varepsilon = \sum_j a_j \cdot X_{ij} + \sum_k b_k \cdot (Z_p \cdot X_{ik}) + \varepsilon, \tag{2}$$

where the a_j coefficient represents the effect of the X_j parameter on the mean speed m_i, and the b_k coefficient represents the effect of the X_k parameter on the standard deviation of individual speeds σ_i. The Z_p value is the standardized normal variable corresponding to a selected percentile; for example, $Z_{50} = 0$ and $Z_{85} = 1.036$. The ε variable represents the normally distributed disturbance term.

The best specification of the OLS speed model is shown in Table 2. Only the results for the significant parameters representing mean speed factors are presented. All the parameters are significant at a 93 percent confidence level and the adjusted R^2 statistic is 0.88. Equation 2 can be further improved by adding site-specific and percentile-specific random effects to avoid bias in estimating the model parameters caused by unknown factors not incorporated in the regression model. The random site variable was significant, indicating that omitting the random effects causes some bias in the model estimation.

The OLS speed model includes eight road characteristics as mean speed factors (seven of those are also speed dispersion factors). A positive sign of a regression parameter indicates that the variable increases the mean speed. The speed model developed in this study, similar to other existing speed models, cannot be used to estimate the direct impact on safety of any change in the road characteristics. The model formulation is not capable of capturing the endogenous relationship between the objective risk and the free-flow speed. A crash rate variable was found to have a negative relationship with the mean speed when included as a parameter in the model, but its estimate was insignificant (p-value was 0.55). The relationship between speed, road characteristics, and crash rate became evident when the significance of the crash rate variable increased with the removal of some of the significant road characteristics from the speed model. The relationship between the road and driver behavior and their effects on speeds and crashes need to be considered in order to better capture the effects on safety.

5.3 Crash Modeling

The crash modeling task evaluated the interaction between the road design and crashes on four-lane highways. Safety is usually measured in terms of crash frequency or crash rate. Poisson and NB regression are often used for modeling crash counts. The NB formulation allows the variance of the counts to be different from its mean value. The Poisson and NB models can be estimated by specifying the Poisson parameter λ_i as a log-linear function of exogenous (i.e. independent) variables. The log-linear relationship for the NB model is given by

$$\lambda_i = \exp(\boldsymbol{\beta} \cdot \boldsymbol{X_i} + \varepsilon_i), \qquad (3)$$

where X_i is a vector of exogenous variables, β is a vector of estimable parameters, and ε_i is a gamma-distributed error term with mean equal to one and variance equal to α^2. Linear regression and nested logit models have been used to estimate crash rate or crash severity, respectively. Readers interested in details about the Poisson and NB regression models are referred to Washington et al. (2003).

The best specification of the NB crash model is shown in Table 2. All the parameters included in the model are significant at a 90 percent confidence level. The rho-squared statistic, a measure of the overall fit of the model similar to the R^2 statistic, is 0.69. The overdispersion parameter was found to be significant, indicating that the variance is different than the mean value and the use of the NB model is appropriate. All the highway segments in the sample have non-zero crash frequencies; therefore, there is no compelling reason to expect that the two-state is present.

The NB crash frequency model includes three road characteristics in addition to the segment length and the traffic volume. A positive sign of a regression parameter indicates that the variable increases the crash frequency of the highway segment. Similar to the speed model, the NB model could not be used to model the endogenous relationship between the objective risk and the free-flow speeds. The mean speed was found to have a negative (and ambiguous) relationship with the crash frequency when included as a variable in the model, and the parameter estimate was insignificant (p-value was 0.18). The relationships between free-flow speeds, road characteristics, and crashes became evident when the significance of the mean speed variable in the model increased with the removal of all the road characteristics, except the traffic volume, from the crash frequency model. If the posted speed limit and the roadside obstructions indicator variables are removed then the mean speed replaces the impact of those variables but the effect is still negative and the model performance diminishes substantially. The model formulation needs to be improved by including the effect of the road characteristics on the crash likelihood and free-flow speeds and the endogenous relationship between crashes and speeds.

5.4 Speed and Crash Rate Simultaneous Modeling

Figure 1 presents the system of simultaneous equations used to explore the relationship between the mean free-flow speeds, crash rates (objective risk), and road characteristics.

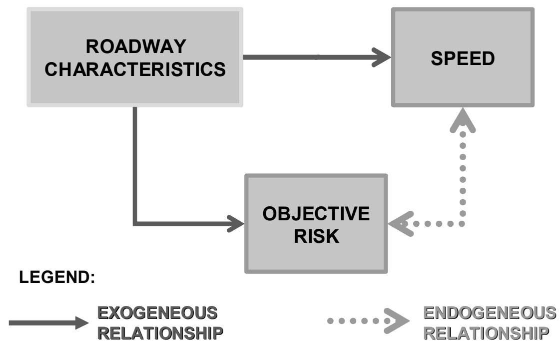

Figure 1: Relationships between System Components

The objective risk, represented with the crash rate, is assumed to be a function of the road characteristics and the speed. This postulated relationship is substantiated with the NB crash model results. Although the NB model failed to include speed as a significant parameter, it is also postulated that the speed plays a significant role in the likelihood of crashes on the road. The influence of speed is definitely apparent as high speeds increase the complexity of the driving task, compromise the driver's ability to avoid a potential crash, and increase the severity of a crash.

The speed selected by drivers on the road, by means of the perceived risk, is assumed to be a function of the road characteristics and the objective risk. This postulated relationship is substantiated with the risk perception study. The study showed that the less hazardous the segment, the more inclined were the subjects to perceive less risk (i.e., feel very safe). The objective risk interacts with the perceived risk to alter the driver behavior on the road (as represented by the selection of speed). Whenever the perceived risk increases, drivers compensate by driving slower and being more alert to the road conditions.

It was proposed that the relationship between the objective and perceived risks and the cyclic relationship between the objective risk, the perceived risk, and the speed be explained by an endogenous relationship between the objective risk and speed in the system. The relationship between the road characteristics and the perceived risk was accordingly replaced by an exogenous relationship between the road characteristics and the speed selected by the drivers. The exogenous relationship between the road characteristics and the speed selected by the drivers is supported with the OLS speed model results.

The system of relationships was formulated using a simultaneous equations model that consists of two structural equations involving two endogenous variables, objective risk and speed selected by the drivers, which are determined within the system. The values of both endogenous variables also depend on several exogenous variables that represent different road characteristics. The exogenous variables are assumed to be determined outside of the system and causal, characterizing the environment in which the endogenous variables are determined (Rudd, 2000). The system of simultaneous equations is formulated as

$$V = \boldsymbol{\beta_V} \cdot \mathbf{X_V} + \lambda_V \cdot R + \varepsilon_V , \quad (4)$$

$$R = \boldsymbol{\beta_R} \cdot \mathbf{X_R} + \lambda_R \cdot V + \varepsilon_R , \quad (5)$$

where V is the mean free-flow speed, R is the objective risk, **X** represents the vectors of the exogenous road characteristics influencing the speed or the objective risk, **β** represents the vectors of estimable parameters, λ represents the estimable scalars, and ε represents the disturbance terms.

The best specification of the system of equations model (in their reduced form) is shown in Table 2. The reduced forms of the simultaneous equations express each endogenous variable in terms of the predetermined variables and disturbances. All the parameters included in the system are significant at a 90 percent confidence level. The adjusted R^2 statistics show that 75 percent of the variability in the mean speed variable and 42 percent of the variability in the crash rate variable are explained by the model.

Table 2: Road Characteristics as Mean Speed and Crash Factors

Variable	System mean speed model	OLS mean speed model	Ordered probit model (1)	System crash rate model	NB crash model (2)
50-mph speed limit	-4.06	-4.84	NS	0.74	NS
45-mph speed limit	-6.02	-5.35	NS	1.36	NS
40-mph speed limit	-8.79	-7.84	NS	2.78	NS
Rural area	3.18	2.58	LR	0.58	NS
Cross-section width	0.04	NS	LR	0.007	NS
Narrow clear zone	-2.24	-2.21	S	-0.41	0.62
Median width	S	0.04	S	S	NS
TWLT median lane	0.36	NS	LR	-0.86	NS
Intersection density	-0.13	-0.39	MR	0.31	0.08
Median opening density	-0.13	-0.51	MR	0.32	NS
Commercial driveways	NS	NS	MR	NS	0.48
Sidewalk	-0.96	NS	NS	2.32	NS
Roadside obstructions	-0.58	NS	NS	1.41	NS
Horizontal curve	-1.65	NS	NS	-0.30	NS
Sight distance	NS	1.26×10^{-3}	NS	N.S.	NS

Notes:
NS = not significant at a 90 percent confidence level.
S = found significant, but effect was included in another variable in the model.
LR = presence or an increase in this variable indicates drivers are more likely to perceive less risk on the road.
MR = presence or an increase in this variable indicates drivers are more likely to perceive more risk on the road.
(1) = Includes only the stated impact of the road characteristics in the risk perception of drivers.
(2) = Parameter estimates included in the NB crash model cannot be compared directly with the other models.

The mean speed system model includes one endogenous variable, seven exogenous variables, and a constant term. The exogenous variables represent the effects of five different road characteristics and the endogenous variable represents the effect of the objective risk on the mean free-flow speed selected by drivers. The objective risk system model includes one endogenous variable, eight exogenous variables, and a constant term. The exogenous variables represent the effects of six different road characteristics and the endogenous variable represents the effect of the mean free-flow speed on the objective risk. A positive sign of a regression parameter indicates that the variable increases the mean speed or the objective risk.

6. Discussion of Results

Two main mean speed and crash rate factors are the intersection and median opening densities. Speed decreases and crash rate increases as any of the two densities increase in the road. This impact is obvious as a higher density of access points will increase the likelihood of vehicles entering and exiting the road and the potential for higher interaction between conflicting vehicles. The system of simultaneous equations assigns similar effects for both density values. In contrast, the OLS speed model assigns a higher impact on speeds to the median opening density with no evident practical justification for this effect. The NB crash model did not include the median opening density as a significant variable, but did include the increasing effect on crashes of high density of commercial driveways. The system also estimated an increasing effect of high density of commercial driveways on crash rate (estimate was 0.91), but was not included in the model because of poor statistical significance (p-value was 0.13).

The presence of a two-way left turn (TWLT) median lane has an increasing effect on the mean speed and a decreasing effect on the crash rate. These two effects confirm the general inferences made about these median lanes and their impact on safety (AASHTO, 2001). Although these median lanes induce a slight increase in the mean speed, their main contribution is the reduction in the likelihood of crash. The presence of a TWLT median lane on the road made drivers perceive less risk. TWLT lanes are typically used to provide a greater sense of separation between opposing traffic lanes and to allow vehicles to enter and exit the road more effectively, reducing the impact on traffic flow. The OLS speed model identified the presence of TWLT lanes as a decreasing speed dispersion factor. Lower speed dispersion is associated with lower crash potential. The system performs a better job than the single-equation models by directly identifying the impact of TWLT lanes on the mean speed and the crash rate.

The width of the cross-section and the roadside clear zone were identified as mean speed and crash rate factors. As expected, an increase in the width of the cross-section and the clear zone contributes to higher mean speeds on the road as drivers perceive less risk when having more separation between the travel lanes and the median and roadside obstructions. The positive impact on crash rates observed in the system for these two variables is indirectly influenced by the increase in the mean speed. The OLS speed model identified a similar reduction in speed due to the narrow roadside clear zones, although it failed to identify the impact of the cross-section width on speed. The safety effect of the roadside clear zone needs to account for the impact of roadside obstructions. The presence of sidewalks, pole lines, and embankments were included in the system. These three roadside obstructions increase the likelihood of crash and therefore reduce the mean speed on the road. Most of the highway segments having these roadside obstructions have a narrow roadside (less than 20 ft). The OLS speed model and the negative binomial crash frequency model failed to incorporate the roadside obstruction variables as significant factors.

The presence of a horizontal curve reduces the mean speed as drivers respond to the extra risk of the change in curvature. No direct effect on the crash rate was identified for the presence of a curve. The impact on crash rates due to the presence of horizontal curves must be attributed totally to its reduction in mean speed. No direct relationship could be attributed between the crash rates and the degree of curvature of the observed horizontal curves. The degree of curvature was insignificant when the variable was included as an exogenous variable in the system. The presence of horizontal curves was not included in any of the single-equation models. The horizontal curves in the sample have a very flat curvature and cannot be considered to significantly increase the likelihood of crashes. Figueroa and Tarko (2004) found that horizontal curves with radii values higher than 1,700 ft do not have a greater impact on the free-flow speeds on two-lane rural highways than the impact caused by the cross-section dimensions and other road characteristics.

The system results show that the speed limit is the strongest mean speed factor. As expected, a lower speed limit (the base speed limit was 55 mph) is associated with lower mean speeds. The system model performs a superior job of providing a more logical estimate for the reduction in mean speed caused by the reduction in the speed limit than does the OLS model. The posted speed limit is also an important crash rate factor. Lower speed limits were associated with higher crash rates in the system. In contrast, the NB crash model did not include any of the speed limits as significant variables.

The increase in the crash rate on the road might appear to contradict the assumption that a factor that reduces the mean speed should also result in a reduction in the crash rate. The effect of the speed limit variable in the system models presents an interesting situation. It is important to note that a mere reduction in the speed limit will not lead to an improvement in the safety of a highway segment, even though a reduction in the mean speed is associated with decreasing speed limit values. The speed limit is associated with many of the road characteristics. Correlation between some of the road characteristics and the speed limit is expected due to the application of design standards and guidelines.

The results of a multinomial logit model developed with the data collected concur with the typical practice of selecting speed limits by using the operating speed, another term for the 85^{th} percentile speed, and the crash history on the road (AASHTO, 2001). The model indicates that higher 85^{th} percentile speeds and lower crash frequencies increase the probability that a highway segment has a 55-mph posted speed limit in the sample. Highway segments with lower speed limits in the sample were also observed to be related to suburban locations; higher intersection, median opening and driveway densities; narrower cross-section widths and roadside clear zones; and the presence of median barriers (typically associated with narrow median widths). The lower speed limit on some of those highway segments might be the end result of an engineering study that identified a safety problem and attempted to reduce the crash rate of an already hazardous highway segment by reducing the speed of drivers on the road. The positive impact on the crash rate cannot be interpreted as a causal relationship between the speed limit and the crash rate. The increasing effect of the speed limit on the crash rate for segments with lower posted speed limits might be triggered by the presence of narrower cross-sections, higher access densities, and more hazardous roadway conditions, compared with the sections with the higher posted speed limits.

A similar interpretation of the impact on the crash rate can be given to the rural area indicator variable included in the system. The positive impact on speed of the rural area indicator is triggered by the presence of higher speed limits, wider cross-sections and roadside clearance distances, and lower densities of access points for sections in rural areas compared to suburban areas. The impact on crash rates is directly associated with the positive impact on the mean speed. The OLS speed model observed the increasing effect on the mean speeds of highway segments in rural locations, although the magnitude of the effect was smaller. The NB model did not include the location variable as a significant factor.

The amount of sight distance on the road was the only road characteristic that was identified in the OLS mean speed model that was not included in the system. The OLS speed model indicated that an increase in sight distance is related to an increase in the mean speed on the road. The system of simultaneous equations identified a similar increasing effect for the sight distance variable (estimate was 0.92 x 10-3), but the variable lacked statistical significance (p-value was 0.51) and was not included in the model.

7. Closure

The system of simultaneous equations shows its effectiveness in better capturing the speed-safety two-way relationship than single-equation models. The system of equations was able to identify the extent of the endogenous relationship between objective safety and speed. Single-equation speed and safety models failed to identify the endogenous relationship between objective safety and mean speed. By failing to identify this endogenous relationship the results from single-equation models provided parameter estimates that are biased and inconsistent, from which any inference made might be invalid.

The interpretation of the relationship between mean speed and objective safety was straightforward from the results of the system of simultaneous equations. The relationship establishes that the mean speed on the road decreases with increasing crash rate and the perception of riskier conditions as represented by the road characteristics. On the other hand, the system crash rate equation includes the effects of the mean speed and six different road characteristics. The relationship establishes that the crash rate increases with increasing mean speed and the presence of riskier conditions as represented by the road characteristics. The first relationship can be convincingly explained on the ground of the theory of rational behavior (or homeostasis). The second relationship can be convincingly explained based on limited human and vehicle performance.

The system of simultaneous equations model provides a substantial improvement in the identification of road characteristics as speed or safety factors, in comparison with single-equation models. The system of equations identified the impact of ten different road characteristics, in comparison with only three characteristics identified in a NB crash frequency model and seven characteristics identified in a OLS mean speed model developed using the same sample.

The simultaneous-equations model presented in this paper did not provide a considerable improvement in the prediction of speed and crash rate estimates which might be attributed to the small sample size used for the study and the potentially large variability of measurement error of the crash rates. Future research could be directed to perform the analysis with a larger sample of highway segments to improve the performance of the models.

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