ANALYSIS OF INCONSISTENCIES RELATED TO DESIGN SPEED, OPERATING SPEED AND POSTED SPEED LIMIT

Stamtiadis, N.
Full professor – University of Kentucky, USA – nstamat@engr.uky.edu
Gong, H.
Research Assistant– University of Kentucky, USA – hgong@engr.uky.edu

ABSTRACT

One of the fundamental elements of roadway design is the design speed, since it has the potential to affect almost every roadway design aspect. Most of the studies that have dealt with safety and speeds typically considered speed limit and thus, little is known about the influence of design speeds on safety. A recently embraced premise for roadway design is the development of such a design where the roadway itself provides the clues to the drivers regarding their operating speeds. Design consistency on most highways has been assumed to be provided though the selection of and application of design speed. It is believed that drivers will make fewer errors handling geometric features that conform to their expectations. The weakness of the design speed concept is that it uses the design speed of the most restrictive geometric element within the section, usually the horizontal and/or the vertical curve of the alignment, without explicitly accounting for the speeds that motorists travel on tangents. A study was performed that has as objectives to examine the relationship among design speeds, operating speeds and speed limits and develop guidelines for selecting the appropriate speeds to minimize any existing discrepancies along these speeds. Roadway sections were selected throughout Kentucky based on the relationship between design speed and posted speed limit (greater or lower) and on the number of lanes (2 or 4). Speed data and roadway geometry data were collected along these sites to allow for the development of the appropriate models. The general conclusion for 2-lane highways is that the operating speed is different than the design speed indicating that there is no agreement between them. For the 4-lane highways there was an agreement between operating and design speeds indicating the absence of any differences. The relationship between operating speed and posted speed limit showed that for all roadways these two speed metrics were different and the posted speed limit was lower than the 85^{th} operating speeds. The safety analysis showed in general that there were no significant safety consequences from the inconsistencies among the various speeds metrics. A set of recommended guidelines is proposed that aim in alleviating potential inconsistencies among these speed metrics focusing on selecting the design speed based on desired operating speeds to avoid possible inconsistencies that could lead to driver errors.

Keywords: design speed, operating speed, prediction models, speed limits

1. INTRODUCTION

Design speed has been the controlling factor in selecting the components of vertical and horizontal roadway alignment since the 1930s. At about the same period, the practice of selecting posted speed limits on statistical analysis of vehicular speeds was initiated (Zegeer and Deacon, 1987). Speed limits have been typically set based on the 85^{th} percentile speed. The intrinsic assumption here is that the driver is able to determine and follow the appropriate speed to travel on the roadway. This assumes that the roadway will provide the driver with adequate information to decide the appropriate speed. Given these basic assumptions, design speeds should be selected in a way that would create a safe operating speed and will not introduce abrupt changes in operating speeds between roadway sections. There are cases however that this principle does not hold. In such cases, the designer needs to intervene and provide additional information to the drivers to assist them in adjusting their speed. This information is typically provided by signs, warning and regulatory, as well as pavement markings.

One of the fundamental elements of roadway design is the design speed, since it has the potential to affect almost every roadway design aspect. Most of the studies that have dealt with safety and speeds typically considered speed limit and thus, little is known about the influence of design speeds on safety (Stuster and Coffman 1998). It could be assumed that there are some relationships between design speeds and speed limits, but it is not feasible to develop a systematic relationship due to the methods used to establish speed limits in many states. Moreover, of interest to highway designers is the determination of whether there are any safety consequences from improper transition between design speeds when entering and exiting a rural community (Stamatiadis et al 2006). Current design approaches for rural highways emphasize speed as a surrogate for quality and efficiency.

A recently embraced premise for roadway design is the development of such a design where the roadway itself provides the clues to the drivers regarding their operating speeds. Therefore, a requirement placed on roadway design is meeting driver expectations by creating a consistent roadway design. Driver expectancy is formed by experience and has a significant influence on the driving task, since it can increase the driver's readiness to complete a task. A consistent speed environment that conforms to driver expectations is desirable to avoid abrupt changes in operating speeds and thus create a safe operating environment. The design speed concept currently being used by designers via the Green Book (AASHTO, 2001) does not necessarily provide uniform profiles for operating speeds on alignments whose design speeds are less than the driver's desired speeds.

Design consistency on most highways has been assumed to be provided though the selection of and application of design speed. It is believed that drivers will make fewer errors handling geometric features that conform to their expectations. The weakness of the design speed concept is that it uses the design speed of the most restrictive geometric element within the section, usually the horizontal and/or the vertical curve of the alignment, without explicitly accounting for the speeds that motorists travel on tangents. A consistent alignment is important because of the relationship that exists between consistency and safety. The inconsistencies that exist on a roadway can produce a sudden change in the characteristic of the roadway (between segments), which can surprise motorists and lead to speed errors. Speed errors result in critical driving maneuvers for motorists and can lead to an increase in crashes.

A common practice has been to set speed limits at the 85th percentile of operating speeds (Fitzpatrick et al 2003). There is a suspicion however that operating and design speeds are often not in agreement. Moreover, posting of speed limits based on operating speeds that are inconsistent with design speed can create potential safety problems. Speed limits have been observed to be posted that are higher than the design speed of the roadway which may also have a safety impact. Therefore, there may be liability issues arising from such designs especially when posted speed limits exceed design speed.

Given these issues, a study was performed that has objectives to examine the relationship among design speeds, operating speeds and speed limits and develop models for selecting the appropriate speeds to minimize discrepancies among them.

2. METHODOLOGY

2.1 Data Collection

The Kentucky Highway Performance Monitoring System (HPMS) database was used as the primary data source for identifying study sections. The 2003 HPMS database was used as this was the most current version available at the time of the study.

Two sample sets of data were identified from the HPMS to identify inconsistencies between operating speed and speed limit. In the absence of operating speed data, design speed as reported by the HPMS was used as a surrogate. The first sample set included sections where the design speed was significantly greater than the posted speed limit. The second sample set included sections where the speed limit was less than the design speed, to identify sections where operating speed would be lower than the posted speed limit. Study sections were initially limited to rural roadways. This constraint was imposed to avoid congestion or traffic control (e.g. traffic signals and stop signs), which curves impact roadway sections through traffic flow and travel speed. The data set was later expanded to include small urban areas (population <50,000) in order to include sections with urban characteristics. Such sections were of special concern to the study team, while still limiting the potential for extraneous impacts to travel speed.

An initial review of sections was completed to identify the sections that met the above constraints. A second review was then completed by reviewing the characteristics of each section to ensure a wide distribution of operational characteristics. These characteristics included design speed, speed limit, functional classification, average daily traffic, and in state geographic distribution. A total of 139 sites were selected for this study. There were 47 sites with design speed less than speed limit, and 92 sites with design speed greater than speed limit (Table 1).

Table 1: Features of Selected Sites

	Design speed > Speed limit		Design speed < Speed limit	
Highway	Rural	Urban	Rural	Urban
2-lane	69	8	46	1
4-lane	4	11	0	0

The speed data was collected from May 2005 to March 2006 during daylight, off-peak periods, and under good weather conditions. The speed collectors were required to record and verify all site information. Vehicle type was identified on site by observation. Free-flow speed data were collected to ensure that the operating speeds measured were only affected by the roadway features. The speed data were collected using a radar gun, and were recorded at the center of each horizontal curve. In order to avoid influencing the driver's operating speeds, the data collectors were located where they could see the measurement point while drivers could not see them. Initially, and based on prior speed collection experience, at least 100 observations were to be taken at each site. However, there are some roads with low average annual daily traffic (AADT). Therefore, fewer observations were typically taken at sites with low AADT.

2.2 Statistical Analysis

A basic assumption for speeds is that the observations obtained from a normal distribution. This assumption needs to be verified for each site. Moreover, for the sites where few spot speeds were obtained, it was more important to check the normality before using the collected data in the analysis. Insufficient spot speed samples cannot represent the real population, and therefore they will likely produce meaningless results. In this study, 17 sites with less than 50 spot speeds were checked.

The normality check procedure includes the Kolmogorov-Smirnov test and probability plotting. The Kolmogorov-Smirnov test is a non-parametric test for goodness-of-fit. It can be used to test whether the distribution of a sample matches a specific distribution, in this case the normal distribution. If the p-value of the Kolmogorov-Smirnov test is less than the significance level considered, the distribution of the sample is not normal at the significance level. If the p-value is greater than the significance level, a probability plot should be used to determine whether the distribution of a sample is normal or not. The software of Statistical Package for the Social Sciences (SPSS) was used for the Kolmogorov-Smirnov test, and Matlab was used for probability plotting. After using the Kolmogorov-Smirnov test and the normal probability plots, 16 of the 17 sites were discarded due to lack of normality. Therefore a total of 124 sites were available for this study.

Some of the past studies on rural two-lane highways used simple linear regression method for developing operating speed-prediction models. In this study, both simple linear and multiple regression methods were used to develop a prediction model for operating speed of passenger vehicles on horizontal curves. The purpose was to obtain the best model by comparing the simple linear regression models and the multiple regression models.

Another element of concern is whether the speed inconsistencies have any safety effect on these roadways. The safety analysis used was a crash rate analysis, which calculated the crash rates for each segment examined and compared them to critical rates. This comparison allows for the relative evaluation of the safety level for each segment as the compare to the statewide average crash rates for similar sections.

Crash data for a three year period was utilized in this analysis. The crashes for each segment for the 2002-04 period were extracted from the Kentucky crash database based on county, route number, and milepoint. Exposure rates were obtained for each site using the site length and the AADT (based on HPMS data). To develop critical rate factors for the first safety analysis, each site was also categorized based on the available critical rates for Kentucky as they had been developed in a previous study (Green et al. 2005). Each segment was identified as a section (if it had length of 0.4 miles or more) or a spot and the corresponding critical rates were identified.

The critical rates are computed using the following formula.

$$C_c = C_a + K(\mathrm{sqrt}(C_a/M)) + 1/(2M)$$

where C_c = critical crash rate; C_a = average crash rate; sqrt = square root; K = constant related to level of statistical significance selected (a probability of 0.995 was used wherein K = 2.576); M = exposure (for sections, M was in terms of 100 million vehicle-miles (100 MVM); for spots, M was in terms of million vehicles).

To determine the critical rate factors, the actual rate was divided by the critical rate. This returned a ratio that, when greater than one, indicates that the location has a rate that is statistically higher than the statewide average rate for that type of highway. This indicates that the location should be further examined to determine if the presence of any particular elements that could contribute to the crashes at the site. The same procedure was conducted for injury crashes only. A third approach was also utilized where speed related only crashes were examined alone to determine whether there is any pattern that could further explain any safety issues that could arise form the speed inconsistencies.

3. DATA ANALYSIS AND RESULTS

3.1 Speed Relationships

The sites examined were rural 2-lane and 4-lane highways. First, the speed relationships were examined for rural 2-lane roads. Of interest here is also the fact that speed limits are frequently set irrespective of the design speed and therefore it was considered appropriate to partition these roadways based upon the relationship between design speed and posted speed limit. Therefore, two additional analyses were completed for 2-lane roads. All 4-lane roadways had a design speed greater than the posted speed limit. In summary, the relationships and models examined were for 2-lane roads, 2-lane roads where the design speed was greater than the speed limit, 2-lane roads where the design speed was lower than the speed limit, and 4-lane roads. To determine the relationships between any two of these speeds, the data was used in similar groupings as before. These relationships were examined using a paired t-test and ensuring normality of the distribution.

3.1.1 Design Speed vs. Operating Speed

The relationship between operating and design speeds varied according to the highway type considered. For 2-lane highways, these two speeds were different and, in general, the operating speed was higher than the design speed. The average difference between operating speed and design speed reached 2.76 mph (operating speed minus design speed). The same trend was also noted for roads where the design speed was lower than the speed limit. However, the average difference between operating speed and design speed was significantly larger, 7.88 mph. For roads where the design speed was greater than the speed limit, the speeds were different but the design speed was greater than the speed limit. The average difference between operating speed and design speed was -8.72 mph (again operating speed minus design speed). For the 4-lane sections and the special cases, there was no difference between the two speeds indicating an agreement between operating and design speeds.

3.1.2 Operating Speed vs. Posted Speed Limit

The relationship between operating speed and posted speed limit showed a uniform pattern. In general, these two speed metrics were different and the posted speed limit was lower than the 85^{th} operating speeds. This was true for all groups considered here except those where the design speed was lower than the posted speed limit. For those sections, the two speed metrics were not statistically significant. This may indicate that when posted speed limits were higher than design speeds, drivers operated based not on design speed but on posted speed limits.

The average difference between these two speed metrics showed a wide variation among the road types considered. For two-lane roads, this difference was 2.44 mph (operating speed minus posted speed limit); for roads with design speed greater than speed limit it was 4.97 mph; for four-lane roadways it was 9.22 mph; and for the special sites it was 4.81 mph.

3.2 Speed Models

One of the objectives of this study is to examine and develop relationships for operating speeds, design speed and speed limits. The same four road groups were utilized here as in the previous section, i.e. models were developed for 2-lane roads, 2-lane roads where the design speed was greater than the speed limit, 2-lane roads where the design speed was lower than the speed limit, and 4-lane roads where the design speed was greater than the speed limit.

Each model was developed aiming to include the best variables capable of predicting operating speed. The variables used in the model development process included the AADT, radius of curve, lane and shoulder width, design speed, speed limits, length of curve, and road width. The linear relationship between operating speed and the inverse of curve radius has been identified in past studies as a predictor for operating speeds. The models were originally developed using degree of curvature because in the Imperial unit system it was the standard descriptor of horizontal curve. The relationship between degree of curvature and radius is an inverse relationship. For these reasons it was deemed appropriate to use the inverse of the curve radius as a predictor here. A model was developed for each variable alone as well as combinations of variables. Each model was evaluated and its ability to predict operating speeds was determined. The most appropriate model was then selected as the “best” prediction.

3.2.1 2-Lane Rural Roads

The variables noted above were considered and evaluated to determine potential relationships between operating speed and geometric features. The variables that showed a potential included the inverse of the radius, length of the curve, and design speed. After eliminating data that considered outliers and thus statistically extreme, a model was developed using 103 sites shown below:

$$V_{85} = 26.903 + 0.495\ DS + 0.003\ LC - 0.437\ DL - (1633.64/R)$$

where V_{85} = 85th percentile speed (mph); R = radius of curve (feet); LC = length of curve (ft); DS= design speed (mph); and DL = design speed minus posted speed limit (mph). The model’s R^2 value is 0.537, indicating a relatively strong ability to predict the operating speed using these variables. The t-ratios for each variable are 6.08 ($p<0.0001$) for DS, 2.98 ($p=0.0036$) for LC, -6.98 ($p<0.0001$) for DL and -3.67 ($p=0.0004$) for R.

3.2.2 2-Lane Rural Roads, Design Speed Lower than Speed Limit

A similar analysis was undertaken for these roadway segments. The same geometric features were used to predict the 85th percentile speed including the inverse of curve radius as noted above. For this model, only two variables were statistically significant: inverse of radius and length of horizontal curve. This indicated that these two variables are significant to operating speed. Using the speed data from the 37 sites, the best model was obtained as shown below:

$$V_{85} = 56.914 - (3883.586/R) -$$

where V_{85} = 85th percentile speed (mph) and R = radius of curve (feet). The model’s R^2 is 0.4398 and t-ratio for R is -5.24 ($p<0.0001$).

3.2.3 Rural Highways, Design Speed Greater than Speed Limit

On these highways, it was determined that the model using as predictors the inverse of radius, the design speed, and the right shoulder width have the best predictive ability. Using the speed data from the 67 sites, the best model was obtained as shown below:

$$V_{85} = 39.295 + 0.203\ DS + 1.024 * RSW - (2949.627/R)$$

where V_{85} = 85th percentile speed (mph); DS = design speed (mph); RSW = right shoulder width (ft); and R = radius of curve (ft). This model had a lower R^2 than the other two models (0.3949) indicating a less strong predictive ability. The t-ratios for the variables are 2.01 ($p=0.0488$) for DS, 2.70 ($p=0.0090$) for RSW, and -3.55 ($p=0.0007$) for R.

3.2.4 Lane Rural Highways

Data only for 14 such segments was collected and all had a design speed greater than the posted speed limit. Although the number of the sites was not adequate for a robust statistical analysis, models were developed to obtain a general understanding the relationship between operating speeds and geometric features on horizontal curves. Additional geometric features, such as median and left shoulder width, might have an impact on speeds for these roadways. Therefore these variables were included in the analysis in addition to the variables used before. Using the speed data from the 13 sites, the best model was obtained as shown below:

$$V_{85} = 46.357 + 1.153 * RSW$$

where V_{85} = 85th percentile speed and RSW = right shoulder width. This was the strongest model (R^2 =0.8482) but the lack of a large sample may diminish the strength of the model. The t-ratio for RSW is 7.84 (p<0.0001).

3.3 Safety Analysis

The safety analysis focused on the evaluation of crash rates and the development of crash rate factors for comparing the sites to the critical crash rates for similar sites throughout the state. The crash rates were developed for each of the four sets of concern that were identified in this study. The distinction between segments and spots based on the length of the segment was utilized here. Since the speed data was collected along specific curves, it was considered more appropriate to examine only the crashes associated with these specific curves instead of considering the cashes of the entire segment. It is reasonable to assume that the given curve may exhibit specific characteristics that are not matched throughout the segment and thus skew the results towards an unknown direction. Based on this distinction, most of the sites were considered as spots due to the short length of the curve.

Among the 37 sites of the 2-lane rural highways with design speed lower than speed limit, 33 were considered as spots (i.e. segment length was less that 0.4 miles) and the remaining were considered as segments. There were 28 spots where no crashes were recorded and the remaining 5 had average crash rates ranging between 0.2 to 3.5 crashes per million VMT. The four segments all had crash rates ranging between 64.1 to 378.8 crashes per 100 MVMT. The examination of the Critical Rate Factors indicated that for all sections in this category there was one segment that had a ratio greater than 1 and most were very small. This indicates that all these sections do not exhibit a pattern any different from similar roads in Kentucky and thus, there is no particular safety issue associated from this speed inconsistency. Similar results were noted for the analysis of the injury only crashes and therefore, there are no special concerns for these sites. The analysis for the speed only related crashes indicated that there were only very few crashes that had as contributing factor speed and therefore, no further conclusions could be drawn.

For the 2-lane rural highways with design speed greater that speed limit, 67 sites were used in the analysis and only one was considered a segment. Among the 66 spots, there were 26 that had no crashes and the remaining had crash rates ranging from 0.1 to 3.6 crashes per million VMT. The only segment had a crash rate of 101.4 crashes per 100 MVMT. The Critical Rate Factors show that there were seven spots where the rates were greater than 1.00 indicating that these spots have rates greater than their similar spots in Kentucky. A closer evaluation of these spots indicated that all but one have large radii and large curve lengths. Moreover, at these spots the operating speeds were higher than the posted speed limit ranging from 2 to 19 mph. It is reasonable to then assume that the larger differences between operating speeds and posted speed limits may contribute to the higher than the statewide critical rates. The analysis of the injury crashes showed a similar trend with 38 spots without any crashes and rates between 0.1 and 2.5 crashes per million VMT. The critical rate factors showed five spots with rates greater than 1.00. Among these five spots, three were different than the spots that had a greater than 1.00 rate in all crashes. These three new spots are also on curves with large radii and long curve lengths. In addition, large differences between operating speeds and speed limit were noted, which may contribute to the higher crash rates. The analysis of the speed only related crashes indicated that there were few spots where crashes could be attributed to speeds. Of interest is the fact that four of the five sites with the high critical rate factors had a crash each that could be attributed to speed. Therefore, the combination of large differences between operating speeds and speed limit, higher critical rate factors, large radii and curve lengths, and speed related crashes may indicate a possible design issue for these spots.

There were 13 sites for the 4-lane rural highways used in this analysis and only one was considered a segment. Among the 12 spots, there were 5 that had no crashes and the remaining had crash rates ranging from 0.1 to 1.6 crashes per million VMT. The only segment had a crash rate of 184.9 crashes per 100 MVMT. The Critical Rate Factors show that there was one spot with a rate greater than 1.00. A closer evaluation of this spot indicated that the operating speeds were higher than the posted speed limit by 5 mph. It is reasonable to then assume that this relatively large difference between the operating speed and speed limit may be a major contributor to crash occurrence and thus contributing to the higher than the statewide critical rates. The analysis of the injury crashes showed a similar trend with 7 spots without any crashes and rates between 0.04 and 0.4 crashes per million VMT. The critical rate factors showed one spot, the same as noted for he all crash rates, with rates greater than 1.00. The analysis of the speed only related crashes indicated that there were few spots where crashes could be attributed to speeds.

4. CONCLUSIONS AND DISCUSSION

Design speed has been the controlling factor in selecting the components of vertical and horizontal roadway alignment since the 1930s. Speed limits have been typically set based on the 85th percentile speed. The intrinsic assumption here is that the driver is able to determine and follow the appropriate speed to travel on the roadway. This assumes that the roadway will provide the driver with adequate information to decide the appropriate speed. Given these basic assumptions, design speeds should be selected in a way that would create a safe operating speed and will not introduce abrupt changes in operating speeds between roadway sections. One of the fundamental elements of roadway design is the design speed, since it has the potential to affect almost every roadway design aspect. Moreover, current design approaches for rural highways emphasize speed as a surrogate for quality and efficiency.

Driver expectancy is formed by experience and has a significant influence on the driving task, since it can increase the driver's readiness to complete a task. A consistent speed environment that conforms to driver expectations is desirable to avoid abrupt changes in operating speeds and thus create a safe operating environment. In general, it is reasonable to anticipate that higher design speeds are associated with larger values selected in several geometric design elements which in turn are likely to result in higher operating speeds. The objective of the analysis completed here aimed in examining the potential relationships and effects of these speeds (design, operating and speed limits) both on operations and safety of roadway sections.

Roadway sections were selected throughout Kentucky based on the relationship between design speed and posted speed limit (greater or lower) and on the number of lanes (2 or 4). This produced three sets of data (there were no 4-lane roadway sections with design speed less than posted speed limit). Therefore, the findings are discussed under this categorization. Speed data and roadway geometry data were collected along these sites to allow for the development of the appropriate evaluation.

The first step involved the evaluation of the relationships between design speed, operating speed and posted speed limit and identifying any possible inconsistencies among these speed metrics. A safety analysis was conducted to determine whether any specific safety issues exist for each of the sections examined. Finally, speed models were developed to allow for the prediction of the 85th percentile operating speed based on the values of the selected design elements.

The relationships between operating speed and values of geometric elements were more uniform. For all values and roadway types examined, larger values of the elements resulted in greater operating speeds. These trends are expected, since it is reasonable to assume that for example a roadway section with a wider shoulder will result in higher operating speeds than a similar road with a narrower shoulder. These trends may indicate that, in general, drivers adjust their operating speeds to the various geometry elements they face. Moreover, this also implies that the use of specific values for these elements could affect the operating speeds and thus this is a bidirectional relationship.

The relationship between operating and design speeds varied according to the highway type considered and the relationship between the design speed and posted speed limit. For 2-lane highways, the operating and design speeds were different and, in general, the operating speed was higher than the design speed. When considering the relationship between design speed and posted speed limit, 2-lane roads with design speed lower than the posted speed limit had an operating speed greater than the design speed indicating the close relationship of speed limit and operating speed. On the other hand, when the design speed was greater than the posted speed limit, the operating speed was lower than design speed again demonstrating the well documented relationship of operating speed and posted speed limit.

The general conclusion for 2-lane highways is that the operating speed is different than the design speed indicating that there is no agreement between them. The current approach for selecting a design speed independent of the desired or expected operating speed may not be conducive in creating a consistent roadway design. It is therefore considered more appropriate to determine these two speeds in concurrence to avoid any possible inconsistencies that could lead to driver errors. The models developed here could be of use in bridging such potential discrepancies.

For the 4-lane highways there was an agreement between operating and design speeds indicating the absence of any differences. The range of design speeds was smaller for these roads (45-70 mph) and most were at the higher end of the range (two-thirds were 55 mph or greater). This may explain the absence of any statistical differences between these two speeds. It should also be noted that the analysis for these roadways was based only on 13 segments, which may not be an adequate sample to reach statistically sound results.

The relationship between operating speed and posted speed limit showed that for all roadways these two speed metrics were different and the posted speed limit was lower than the 85th operating speeds. This was true for all groups considered here except those where the design speed was lower than the posted speed limit. For those sections, the two speed metrics were not statistically significant. This may indicate that when posted speed limits were higher than design speeds, drivers operated based not on design speed but on posted speed limits. In general, the relationship between operating speeds and posted speed limit held true for these sections as it was the case from previous studies.

The safety analysis showed various results with a small number of sites exceeding the critical crash rates. However, the analysis showed that in general there were no significant safety consequences from the inconsistencies among the various speeds metrics. There were very few sections with critical crash rates greater than 1.00 indicating that they have a crash rate greater than the statewide average for similar roadway sections or spots. It should be noted though, that this finding does not allow for the continuation of designing and constructing roadway segments where these inconsistencies are intentionally present.

The models developed showed in general that a few design elements have an ability to predict the operating speeds along roadway segments. For 2-lane highways, design speed, length and radius of curve and the difference between design speed and posted speed limit are the predictive variables. Models developed for the roadway sections based on the relationship between design speed and posted speed limit used similar variables. For the roads with design speed lower than speed limit, only the radius of the curve was an acceptable predictor, while for the roads with design speed greater than speed limit, the design speed, curve radius and right shoulder width were used. Finally, for 4-lane highways only the right shoulder width was a good predictor.

All these models have the ability to determine the operating speed of a roadway section given the values selected for the corresponding design elements. However, there are several limitations of these models that should be noted here:

1. The models are only applicable for sections with a horizontal curve. Even though the presence of the curve radius could allow for predicting the operating speed for tangent sections by using infinity as the radius of the curve, the validation of this has not been completed and should be in general avoided.
2. The range of AADT for these models is 400-15,000 for 2-lane highways and 5,000-37,000 for the 4-lane highways. The use of these models for roadway sections outside of these ranges is not recommended without any additional validation.
3. The range for design speeds was 30-70 mph for 2-lane highways and 45-70 mph for the 4-lane highways. Similarly, the range for speed limits was 25-55 mph for 2-lane highways and 35-55 mph for 4-lane highways. As noted above, the use of these models for sections beyond these ranges should be conducted cautiously.
4. The models developed for the 4-lane highways are based only on 13 sections and therefore should be used cautiously.

An interesting element identified in the relationships between speeds and geometric features is the presence of the right shoulder width. This geometric element was a significant variable in the speed prediction models. This finding underscores the importance of this element in assisting the driver to select the appropriate operating speed. However, the paradox is that typically wider shoulders have the potential to provide the driver with additional space to correct any errors and avoid a crash. This finding therefore poses a larger dilemma for the designer in selecting the appropriate shoulder width that will balance these two design priorities.

An important aspect of these findings is that sign of the difference between design speed and speed limit (positive, i.e. greater, or lower) plays an important role. In general, for roadways with design speed lower than speed limit most of the trends did not hold and no significant models were developed. This may be indicative of the larger variation of the values used for the various geometric elements examined and may point towards a greater design inconsistency. Moreover, the absence of any negative safety indications does not automatically guarantee that these and similar sections will not exhibit any problems if this practice continues.

The objective of this work was develop recommendations based on the findings aiming to alleviate some of the inconsistencies between operating speed, design speed and posted speed limit. The analysis conducted indicated that there were some relationships between operating speeds, where greater values for these features resulted in larger operating speeds. This trend is indicative of the influence of specific values of a geometric element on the drivers' operating speeds. Similar relationships were examined and identified between these geometric features and design speed. However, these trends were not apparent for roadways where the design speed was lower than the posted speed limit. The roadway context and the desired operating speed should be closely evaluated and determined from the outset to allow for avoiding scenarios that lead to speed discrepancies. It is therefore recommended that the desired operating speed is first determined and been considered as an element in selecting the roadway design speed. This will allow for a reduction, if not elimination, of the differences between these speed metrics.

It seems that it is imperative to consider the desired operating speed as part of the design speed choice to avoid any large differences between operating speed, design speed, and posted speed limit. The models developed here can facilitate this for sections where a horizontal curve is designed and allow for an iterative process to minimize possible discrepancies among these speed metrics.

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