Research Report
KTC-06-12/SPR286-05-1F

KENTUCKY TRANSPORTATION CENTER

ANALYSIS OF INCONSISTENCIES RELATED TO DESIGN SPEED, OPERATING SPEED, AND SPEED LIMITS

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Analysis of Inconsistencies Related to Design Speed, Operating Speed, and Speed Limits

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16. Abstract

The objective of this research was to examine the relationship among design speeds, operating speeds and speed limits and address safety and operational concerns regarding the presence of disparities among these speed metrics. 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.

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EXECUTIVE SUMMARY

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. In addition, specific issues dealing with the use of two-way left-turn lanes in high speed facilities and the use of curb and gutter were of concern to the Study Advisory Committee (SAC). The ultimate goal of the study is to answer these issues and develop guidelines on determining the appropriate design speed based on the type and location of the roadway.

The literature review showed that the concept of using design speed as the main criterion for designing the various roadway elements leads to discrepancies among the design speed, operating speed and posted speed limits. Ideally, it is preferred to have the same or similar values for all the three speeds. However, in reality this is not the case. The design of roadway elements is primarily carried out by an assumed design speed. Research to date has reported that this assumption can be made on several factors that include legal speed limit, anticipated operating speed, terrain, accident history, functional classification and traffic volumes. However, in most cases the design speed does not match with the operating speeds, creating safety issues.

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 analysis involved the examination of trends of the various geometric features identified in relation to the design and operating speeds of the sections. Models that would allow for the prediction of the 85th percentile operating speed were then developed to provide a means for estimating the impacts of the various choices on the values of the design elements selected. The next 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. Finally, a two-level safety analysis was conducted to determine whether any specific safety issues exist for each of the sections examined and to develop prediction models for crash occurrence.

The trend analysis for the design speed showed that there are some relationships between design speed and the various geometric elements. For most of these elements, the general assumption that greater design speeds lead to larger values for the elements selected seems to hold. However, for roadways where the design speed was lower than the posted speed limit there was no apparent trend for any of these 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 may indicate that, in general, drivers adjust their operating speeds to the various geometry elements they face.

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. 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 85th operating speeds. In general, the relationship between operating speeds and posted speed limit held true for these sections as it was the case from previous studies.

Similar conclusions regarding the discrepancies among speeds could be drawn for the special sections recommended for evaluation by the SAC. Roadway sections with curb and gutter showed that, in general, the design speed was greater than the operating speed and the operating speeds were greater than the posted speed limit. The segments with TWLTL exhibited similar trends as well but the differences were smaller than those observed for the curb and gutter sections. Large differences between posted speed limit and design speed were observed for both roadway types which are likely the contributing factor in the discrepancies among these speed metrics. However, it should be noted that the design speed obtained may not be accurate due to HPMS entry errors and these findings should be viewed cautiously.

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. For 4-lane highways, only the right shoulder width was a good predictor. The small number of segments used for these models may also have prohibited the inclusion of other variables and thus these models should be used cautiously.

The safety analysis showed various results and in general there were no significant safety consequences from the inconsistencies among the various speeds metrics. There were very few sections with critical rates greater than 1.00 indicating that they have a crash rate greater than the statewide average for similar roadway sections or spots. The sections in the special sites (as they were requested by the SAC) had no sections with critical rates greater than 1.00 indicating that the speed inconsistencies do not lead in general to safety problems. It should be noted though, that this finding does not promote continuation of designing and constructing roadway segments where these inconsistencies are intentionally present.

A set of recommended guidelines is proposed that aim in alleviating potential inconsistencies among these speed metrics. As noted above, design speed has the potential to predict the operating speed. However, 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.

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 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. 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. 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. 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, 1994) 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. 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. Moreover, similar safety concerns have been raised by the Transportation Cabinet regarding roadway segments where the operating speed is greater than the posted speed limit.

In addition to the issues noted above, additional specific issues were raised by the Study Advisory Committee (SAC) that had to be addressed as part of this research. These issues focused on whether flush medians should be used for speeds greater than 45 mph and determining appropriate locations for using curb and gutter sections.

Given the issues presented here a study was performed that has 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. The ultimate goal of the study is to answer the issues posed by the SAC and develop guidelines on determining the appropriate design speed based on the type and location of the roadway.

This report is organized into 5 chapters, including introduction, literature review, methodology, conclusions, and recommendations. The introduction describes the background of the study and research objectives. The literature review discusses previous research. The methodology chapter develops three operating speed prediction models, and discusses the relationships among operating speed, design speed, and speed limits. The conclusion chapter summarizes the study effort and findings while the last section provides recommendations applicable to highway design and answers to the SAC questions.

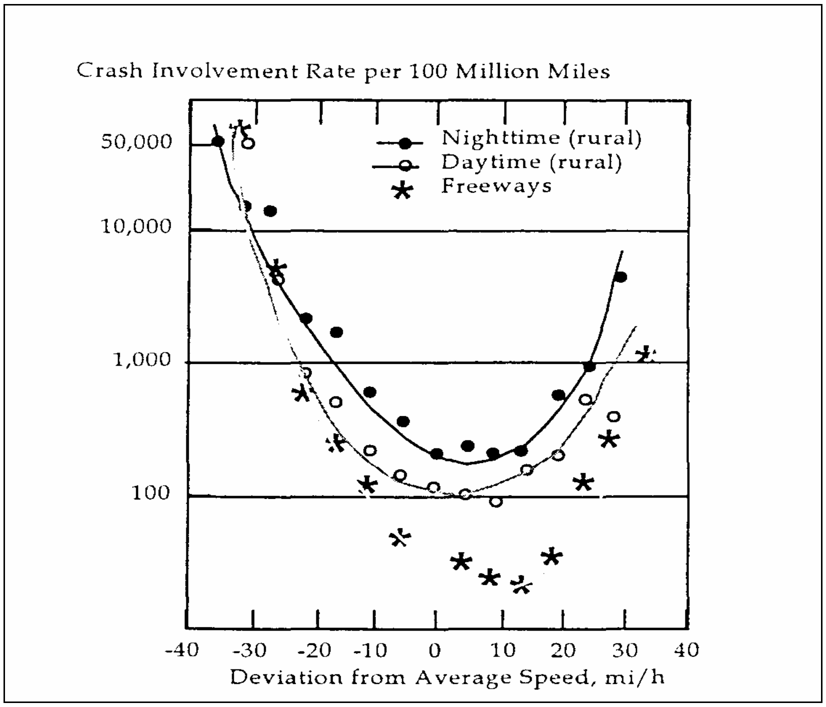
2 LITERATURE REVIEW

In order to develop roadway sections that are consistent in design, there is a need for design speed, operating speed and posted speed limit to be reasonably similar. By doing so, a safe and consistent speed environment that conforms to driver expectations can be created. The current design process, as it is promoted in “A Policy on Geometric Design of Highways and Streets” (Green Book) is inconsistent because it uses the design speed of the most restrictive geometric element (such as a horizontal or vertical curve) for the design of roadways. Such an approach pays little attentions to transitions between curves and tangents and therefore can cause an abrupt change in the driving pattern, which in turn can lead to speeding related errors. This literature review provides a valuable insight on the research conducted to date in regard to these three different speeds and their potential safety implications from inconsistencies among them.

There are several factors that could affect speed related to the driver (age, gender, attitude, perceived risks), environment, vehicle and roadway (geometry, transition, weather). Of all these factors driver attitudes and behavior, road characteristics and environmental conditions seem to be relevant to speed research. As was observed by Solomon (1964), the mean speeds of young drivers, out of state vehicles, buses and latest model passenger vehicles were higher. A similar study conducted by Fildes et al. (1991) found that younger drivers, drivers without passengers, drivers of new cars, drivers traveling for business purposes and high mileage drivers were more likely to drive faster than average and exceed the speed limit. Mustyn and Sheppard (1980) found that more than 75% of drivers claimed to have driven at speeds greater than the posted speed limit as the roadway was permitting them to do so. According to the participants of the study, crossing the speed limit by 10 mph was not an unlawful thing to do but they considered driving in excess of 20 mph as a serious offense.

2.1 Speed and Safety

Safety implications due to high speed exist because speeding reduces the available reaction time and could result in a crash. Stuster and Coffman (1998) conducted a synthesis of safety research related to speed and speed management. In this synthesis they looked at various studies that relate crash rates with change in mean speeds, change in speed at impact and change in posted speed limits A landmark study used 10,000 crashes to examine and define a relationship between vehicle speed and crash incidence on rural highways (Solomon, 1964). A relationship was identified in the form of a U- shape curve between the deviation from the average travel speed and crash rate per 100 million miles. According to this curve, crash rates were lowest when the travel speeds are close to the mean speed of the traffic. However, as the deviation of the travel speed from the mean speed increases in excess of 15 mph, the likelihood of being involved in a crash also increases. One other important observation from this curve is that crash rates decrease with an increase in speed, but this fact only holds good as long as the speed of the vehicle is not above 65mph. Later, Cirillo (1968) confirmed Solomon’s research by conducting a similar analysis on 2,000 vehicles involved in daytime crashes on Interstate freeways. This is illustrated in Figure 1. The analysis was limited to two or more vehicles traveling in the same direction.



Source: Solomon, 1964 and Cirillo, 1968

Figure 1: Crash Involvement rate by deviation from average travel speed

In defense to earlier studies, researchers emphasized speed variance, rather than absolute speed, as the primary culprit in the incidence of crashes. Speed variation is defined as a vehicle's deviation from the mean speed of free-flowing traffic.

The speed of the vehicle also influences the severity of the crash. An early study showed that the severity of a crash on rural roads increased with an increase in speeds (Solomon, 1964). This happened at a faster rate at speeds over 60 mph. The crashes occurring at speeds more than 70 mph mostly resulted in fatal injuries. Another study revealed that chances of injury in a crash depend on the change in impact speeds (Bowie and Waltz, 1994). The study noted that when the change in speed at impact was less than 10 mph, the chances of a moderate or more serious injury to occur were less than 5 percent. This probability increased to 50 percent when the difference in speed at impact exceeded 30 mph. Joksch (1993) noticed that the probability of a car driver being killed in a crash increased with the change in speed to the fourth power.

Studies have shown that changes in posted speed limits play a minor role in the variation of number of crashes. However, a study in Michigan examined that the alteration of speed limits on low and moderate speed roads had little effect on crash rates (Parker, 1992). In another study Parker (1997) analyzed 98 sites in 22 states in the US where speed limits were altered and also showed insignificant figures related to total or injury crashes. On the contrary, after reviewing several international studies, Finch et al. (1994) suggested that for every 1 mph change in mean speed, the number of injury crashes increased by 5 percent.

Another influencing factor on travel speed is the roadway characteristics. Warren (1982) reported that the curvature, grade, length of grade, number of lanes, surface condition, sight distance, lateral clearance, number of intersections and built-up areas near the roadway are significant factors that could contribute to the speeds at which drivers operate their vehicles. In another study, Warren and Tignor (1990) found that the number of access points and nearby development such as proximity to tall objects to the road has the greatest influence on vehicle speeds. Research by Fildes et al. (1987, 1989) found that road width and number of lanes are the two most important characteristics that influence the operating speed. Besides these factors there are always the environmental conditions. Reduced visibility due to fog has been found to cause a 6 mph decline in mean speeds on a freeway in Minnesota (CRC, 1995). Greater speed reductions were observed when weather conditions have gotten worse. Even windy weather plays a vital role in slowing down vehicles. This is exactly what Liang et al. (1998) have found out in a study that showed that drivers reduced their speeds by 0.7 mph for every mile that the wind speed exceeded 25 mph.

2.2 Design Speed Issues

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. As previously used, 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. When this principle is violated, the designer needs to intervene and provide additional information to the drivers to assist them in adjusting their speed.

The Green Book suggests the use of design speed as a guiding factor in the design of any roadway section. Recently, designers are opposing this view for several reasons. One of the reasons is the lack of consistency in its use. In a recent study Fitzpatrick and Carlson (2002) examined the selection of design speed values by DOT’s and they found that several factors exist. These include legal speed limit, legal speed limit plus a value (5 or 10 mph), anticipated operating speed, terrain, accident history and incremental costs in addition to the design guidelines suggested by AASHTO. Other studies (Fitzpatrick et al., 1995, 1996, 1997) also reported that the above factors were taken into consideration for determining the design speeds. Fitzpatrick et al. (2003) also examined the order in which various factors were prioritized by state DOT’s to determine the design speed. For a roadway most DOT’s start with functional classification, legal speed limit, legal speed limit plus 5 or 10 mph, traffic volume, and end with anticipated operating speed. It is important to note that the anticipated operating speed is at the bottom of the list and it has not been seriously considered.

In regard to the adoption of design speeds, Krammes (2000) reported that AASHTO’s minimum design speeds for arterials on rolling terrain and for collectors on level and rolling terrain underestimated the desired speed of today’s drivers. He observed that AASHTO’s policy will not guarantee a full compliance between design speed and operating speed if the design speed is less than 62.1 mph. To correct for this discrepancy Fitzpatrick and Carlson (2002) recommended design speed values for rural two-lane highways, which were modified from those recommended by AASHTO. They suggested the use of anticipated operating speed or posted speed plus 10 mph as the design speed.

After reviewing the standards of international design speeds for roadway geometric design, Polus et al. (1998) observed that the AASHTO design policy controls only the minimum values for design speed and encourages the use of above minimum values. This may currently underestimate the driver's desired speeds. Also, in the classical design speed concept the policies adopted for maximum superelevation rates vary from state to state and from roadway to roadway. These variations might influence driver's speed selection on horizontal curves and may increase the disparity between design and operating speeds. The review also mentioned the standards being adopted in several other countries for roadway design. Germans use both design speed and 85th percentile operating speeds in designing rural roadways. They use design speed as a guiding factor to determine the horizontal and vertical features of an alignment and the 85th percentile operating speed to determine the superelevation rates and stopping sight distances. Swiss engineers use speed profile along an alignment to check for alignment consistency. British designers do not follow the concept of functional classification but they emphasize the effects of alignment and layout (cross-section and access control) constraints while selecting their design speed. Australians use 85th percentile speed as the design speed for low-speed alignment (i.e., less than or equal to 52.5 mph) and traditional design speed procedures in designing their high-speed alignments (i.e., greater than or equal to 62.5 mph). US engineers have a range of design speeds to select among those recommended by AASHTO which are based on functional classification. However, there is a tendency for selecting high speeds, a practice that often disregards driver's desired or operating speeds. Also AASHTO's policy on design speed selection lacks a feedback loop in which the driver speed behavior resulting from the designed alignment can be estimated and compared with the assumed design speed. In general, every country surveyed uses design speed for its design process and one-third of them use the same procedure for both high-speed and low-speed alignments. The authors concluded that AASHTO should conduct further research on the distribution of driver's desired speeds on rural highways to recommend changes for the suggested minimum design speeds. Research should also be undertaken to fully develop and validate the speed profile procedures for evaluating alignment inconsistencies.

In the design of roadway sections Venezuela uses the Feedback Loop Procedure. Andueza (2000) proposed a speed selection approach as outlined below:

1. Select a design speed as a function of all factors
2. Divide a road into analytical sections of at least 3 kilometers long and assign design speeds
3. Construct a speed profile diagram using the set of prediction models for speeds on tangents and curves.
4. Adjust the elements of the geometric design based on these speed profiles to obtain a layout with a more uniform speed. This way, situations that are considered unsafe can be eliminated
5. Design each element with a speed derived from the adjusted speed diagram

Harwood et al. proposed a general design procedure based on a literature review (2000). The steps of the procedure are:

1. Select a design speed first
2. Develop a preliminary design based on the selected design speed
3. Determine the projected operating speed and compare it with the design speed
4. If the operating speed is higher than the design speed, the designer would select a higher design speed and go back to step 2, modify the geometric design, the traffic control plan, and other characteristics of the facility until consistency. If the operating speed is less than

or equal to design speed no adjustments are needed and the prepared preliminary design in Step 2 can be further developed.

A conceptual framework for improving the AASHTO's concept of design speed was presented by Donnell et al. (2002). At first, the desired operating speed could be determined based on the functional class, topography and land use pattern of the roadway. Then the design speed is calculated from the design and operating speed models. The design speed model uses a speed that is above or equal to the design speed recommended by AASHTO. The operating speed models use a speed that is based on the 85th percentile speed of that section. Using these models, the alignment consistency is checked by establishing ranges of acceptable differences. If they are consistent, the roadway will be constructed based on the recommended speed otherwise the desired operating speed will be recalculated and the process will be repeated until consistency is obtained. Once the roadway is opened for operation, speed limits will be set and operating speeds shall be observed. The collected data shall be used as reference for the determination of future design speeds.

Polus et al. (1998) conducted a survey where discrepancies between design speed and actual operating speed were observed. The study found that in general, the operating speeds were lower than the design speeds on high-speed roadways. However, the operating speeds were higher than the design speeds on low-speed roadways. A similar conclusion was drawn in another study where it was shown that the 85th percentile speeds exceeded the design speeds on both horizontal as well as vertical curves (Fitzpatrick et al., 1995). This means that at these sections the operating speed of the drivers is greater that of the design speed. A more recent study reported that design elements such as radius, degree and length of curve, lane width, access density, hazard rating and grade have a relationship with operating speed (Fitzpatrick et al., 2003). The study also concluded that most of these design elements demonstrated minimal impact on the operating speed unless a tight horizontal or vertical curve exists.

Using the horizontal components of roadway, Ottesen and Krammes (2000) found a relationship between design speed and operating speed. Their study revealed that tangent speeds on level roadways were higher than on rolling terrain. Also degree of curvature, length of curvature and deflection angle (degree of curvature times the length of curvature) have significant effect on curve speed. On the other hand, sight distance, approach tangent length, preceding degree of curvature, superelevation rate, lane width and pavement width were not statistically significant predictors. The difference of the 85th percentile speeds of the inside and outside lanes of a roadway is not significant. When the degree of curvature along a curve is less than or equal to 4°, the speeds on long tangents and curvatures differ insignificantly.

2.3 Operational Speed Issues

The use of operating speed as a replacement of the design speed has recently been discussed (Krammes, 2000). The need to reevaluate the use of the design speed as suggested in the Green Book has also been argued and European practices can be used as models (Krammes, 1994 and Stamatiadis, 2000). The differences between design and operating speeds were also addressed in Special Report 214, where procedures for addressing this problem were discussed (TRB Special Report, 1987). Disparities between speeds create some of the problems in design consistency and are central to resolving that issue. A recent report that examined the relationship between operating and design speeds for urban areas concluded the use of operating speeds as a controlling design speed produces more consistent designs (Poe et al., 1996).

A Nebraska study examined the operating speeds at 70 vertical curve sites on horizontal tangents and showed that operating speeds are affected by horizontal curves (Schurr et al. 2000). The mean, 85th and 95th percentile speeds were used to perform statistical analysis on the collected speed data. At the curve mid point, the 85th percentile speed decreased by 1 mph for an increase in deflection of 10 degrees. With an increase in deflection of 12 degrees, the 95th percentile speed decreased by 1 mph. This implies the perception that large deflections in horizontal curves are considered to be severe. Also it was noticed that an increase in the length of the curve resulted in an increase of mean and 85th percentile speed. At the mid point of the curve, for a 1000 ft increase in curve length, the 85th percentile speed increased by 4 mph and the 95th percentile speed increased by 3 mph.

Medina and Tarko (2004) by representing the percentile speed as a linear combination of the mean and the standard deviation an advance method of modeling was developed. An ordinary least squares model for panel data was used to predict the free- flow speeds in two-lane rural highways. A generalized least squares model that considers random effects was used to predict free-flow speeds on four-lane rural and suburban highways. Instead of the particular percentile, the entire speed distribution was utilized to develop these models. The 2-lane rural roads model identified the posted speed limit and the widths of gravel and untreated traversable shoulders for tangent sections, and degree of curve and the superelevation rate for horizontal curves, as the strongest mean speed and speed standard deviation factors on two-lane rural highways. The four-lane and suburban roads model identified the posted speed limit, the intersection density and the median width as the strongest speed factors on such highways. The developed models predict any user-specified percentile speed, involving more design variables than traditional least-square models and separate the impacts on mean speed from the impacts of speed dispersion. Through evaluation of the data collected it was found that in most cases the 85th percentile speeds on two-lane rural highway tangents exceeded the inferred design speed by 19 to 28 mph and horizontal sections exceeded by 5.1 to 15.8 mph. All the sites observed in four-lane highways had 85th percentile speeds higher than the posted speed limit. The authors suggested that the current design policy must be modified in order to avoid the setting of posted speed limit higher than the design speed, and to consider the operating speeds and potential crash experience.

The Highway Capacity Manual (HCM) recommends a process for estimating the free-flow speed of multilane highways based on posted speed limits. However, a recent study indicated that this approach does not adequately estimate the free-flow speed for higher speed limit conditions (Dixon et al., 1999). The study aimed at developing a correlation between posted speeds and actual field measured free-flow speeds for rural multilane roads. Free-flow speed can be considered as an average travel speed a single vehicle travels with no other vehicles present on the segment of road. A conclusion of the study indicated that free-flow speeds do not seem to affect operating speeds. The HCM process estimates free-flow speed using either the 85th percentile speed or the posted speed limit. The study concluded that for low volume rural conditions with heavy vehicle percentages up to 30 percent of measured free-flow speeds are not significantly impacted due to the presence of heavy vehicles in generally level terrain. On the other hand, higher traffic volumes often adversely affect the speed at which a motorist can travel and as volumes increase, speeds remained generally constant with only a slight increase. Access points are probably the most critical element in reducing free-flow speeds. Moreover, access control has a positive effect on improving safety, since it reduces the number of conflict points.

Dixon et al. (1999) studied the relationship between posted speed limit and free-flow speed for rural multilane highways in Georgia. By using speed data collected for two speed limit conditions at the same location, they were able to determine that posted speed limits of 55 mph and 65 mph directly influence the free-flow speeds. A finding of the research was that an increase in the posted speed limits results in an increase of the operating speeds. An alternate relationship of this study is that the free flow speed may be estimated as 91 percent of the 85th percentile speed for both 88.6 and 104.7 km/h (55 and 65mph) conditions observed. Lu et al. (2003) studied multi-lane, nonlimited-access arterial roadways in urban and suburban areas of Florida. His findings were that the 85th percentile speeds are 5 to 10 mph higher than the posted speed limits. On the urban arterials, operating speeds were rather less sensitive to the posted speed limit as compared to other types of roads. Therefore, lowering the speed limit would not necessarily reduce operating speeds.

Another study conducted with data collected in Indiana, reported that change in speed limits had a significant effect on average speed, 85th percentile speed and speed dispersion (Khan and Sinha, 2000). The study concluded that, in general, the change in speed limit has a greater impact on rural roadways than on urban streets. The study also confirmed that the 85th percentile speeds are higher than posted speed limits irrespective of functional classification or geographic location of the roadway. The same finding was documented by Chowdhury and Warren (1991). They collected operating speeds at 28 curves on two-lane highways. The study noted that the operating speeds were higher than the posted speed limits and that the advisory signs did not have significant effect on operating speeds. However, Schurr et al. (2000) found that mean speed at the midpoint of horizontal curves is influenced by posted speed limit.

Methods have been developed to estimate the operating speeds of vehicles. Based on the field data collected in South Africa, Bester (2000) developed a methodology to determine truck speed profiles in mountainous and rolling terrain. In his model it was assumed that the drivers use a constant amount of power. This model is helpful in determining the consistency between the projected operating speeds and the selected design speed of a roadway. Mathematical models were developed by Andueza (2000) to estimate the vehicular speed (mean speed and 85th percentile speed) on curves and tangents in mountain terrain. From these models, it is observed that mean speed and 85th percentile speed on horizontal curves were inversely related to the radius of both the current curve and the preceding curve. A direct relation also existed with the sight distance of the curve was also noted. On tangent sections, the two kinds of speeds were found to be inversely related to the radius of curvature of the preceding curve and are directly related to the length of tangent traveled to the current curve.

2.4 Speed limit Issues

An issue that poses problems, in some instances, is the method with which speed limits are determined. For most states, speed limits are typically set at the 85th percentile of operating speeds. In transition zones from rural to urban areas, speed limits are often posted purposely low to account for local policies. Such a policy may violate driver expectancy if it is not accompanied by other visual clues. A study that attempted to assess the speed limit criteria indicated that 70 percent of drivers did not comply with the posted speed limit, in free-flow conditions (Harkey et al., 1990). Therefore, by simply lowering the speed limit, drivers do not adjust their speeds accordingly and there is a need to use other methods to achieve this objective. Such methods include traffic calming devices, reduced lane widths, planting trees or shrubs or changing the type and color of pavement. All of these devices may facilitate the transition from rural to urban environments and convey a stronger message to the driver than the posted speed limit sign. A recently completed study also documented problems from improper transition between rural and built-up areas (Stamatiadis et al, 2006). The study concerned that there is a need to renew current practices and establish improved design for such areas.

Usually the posted speed limit is taken as the 85th percentile of the operating speeds. Fitzpatrick et al. (2003) found that 85th percentile operating speeds are higher than the posted speed limits and 50th percentile operating speeds are close to the posted speed limit. The study has noted that a large portion of free flow vehicles (37 to 64 percent on rural and 23 to 52 percent on suburban or urban roadway) traveled at speeds no higher than the posted speed limit. The data used in this study clearly indicates that at most sites the 85th percentile speeds exceeded the posted speed limit.

Often times expensive and time consuming speed studies have to be conducted to determine the 85th percentile speed. To overcome this resource-consuming dilemma, models utilizing the back-propagating Artificial Neural Networks (ANNs) were developed to predict the 85th percentile speeds on two-lane rural Kansas highways (Najiar, 2000). The parameters of this model are shoulder width, shoulder type, ADT and percentage of no passing zones. The study revealed that the model predicts the 85th percentile speeds with 96 percent accuracy.

In 1987 several states have changed their interstate speed limits from 55 mph to 65 mph. The "before" and "after" impacts of this change were statistically analyzed showing that for passenger cars the mean operating speeds increased with an increase in speed limits (Garber and Gadiraju, 1992). However, the 10 mph increase in the posted speed limits resulted only in a 1 to 3 mph increase of mean speeds. Speed dispersion for cars decreased with an increase in posted speed limits. It should also be noted that the majority of these studies were conducted on interstate highways and only a few have checked the effects of changing speed limits on low speed nonlimited-access highways.

In an article by Whitten (1996), the concepts of setting speed limits in the state of Texas were explained. The state of Texas, like many other states, sets its speed limits by the 85th percentile speed. The article made note of an important fact that 55 mph and 65 mph were the maximum speed limits set by the federal law and any other speed limits were based on the interpretations of the specific traffic studies. When this law was repealed, speed limits excluding those posted speed limits based on traffic studies became 70 mph, unless a traffic study justifies a lower speed limit. TxDOT engineers have the authority to deviate from the 85-percentile speed by a maximum of 5 mph, but if there is a roadway section that has more accidents than the statewide average, the speed limit can be lowered by as much as 7 mph. The 85th percentile speed test is important in keeping the department from establishing speed limits that are too low. Lower speeds will often be disregarded by the public. The myth about an increase in speed limits causes an increase in accidents was proved false by reports done by TxDOT for four years after the speed limit was raised to 65mph (1987 on rural interstates). In this report it was noted that number of accidents increased a little, but actual rate of accidents had no significant change.

In a special report, the reasons for the regulation of driver speeds were mentioned (TRR 254, 1998). The primary reason is the significant risk drivers impose on others. Another reason for regulating speed is derived from the inability of some drivers to correctly judge the capabilities of their vehicles and to anticipate roadway geometry and roadside conditions sufficiently to determine appropriate driving speeds. The final reason for regulating speed is related to the tendency of some drivers to underestimate or misjudge the effects of speed on crash probability and severity. Speed limits also affect safety in at least two ways. First, they act as a limiting function on speed and reduce both the probability and the severity of crashes. Second, they act as a coordinating function by reducing the dispersion in speeds and thus reduce the potential for vehicular conflicts. It was reported that the behavior cannot be altered by mere change in signs. This can only be achieved by the proper enforcement of law. Depending on the necessity, enforcement can be imposed for shorter intervals of time or over longer periods.

To force drivers to travel at posted speed limits, the concept of transitional speed zones has been implemented. Hildebrand et al. (2004) reviewed studies that have examined the effectiveness of transitional speed zones. At 13 selected sites, 11 percent of drivers who were in transitional speed zones were within the speed limits and 37 percent were on either side of the transitional zone. The mean speed dropped in the transitional zone but, mean speeds at the start of the lowest speed zone were higher than the speed limit. Another observation that was made is that the speed dispersion in transitional zones did not increase. The transitional zones are able to reduce operating speeds at the onset of the lower speed zone but there was little difference compared to those sites without a transitional zone.

2.5 Relationships among speeds

Numerous models for rural two-lane highways have been developed in the past decades to predict operating speed and speed differential based on geometric features. Misaghi and Hassan (2005) listed the models developed in the past 50 years and Appendix A summarizes their findings.

Among the 28 models developed, 26 were based on speed prediction of passenger vehicles, and 27 studies used the 85th percentile speed as the predictor to represent the operating speed. Early studies directly used the curve radius as the predictor. Later studies used a larger number of predictors which mainly consisted of roadway geometric features. In some models, traffic and pavement information were also introduced as predictors. Based on the models shown in Appendix A, the variables that significantly affect operating speed include: radius of the curve, length of the curve, length of the preceding and successive tangents, grades, superelevation, average daily traffic volume, pavement condition, approach speed, and speed limit. Few studies also developed models for predicting the speed of trucks.

In addition, 27 out of the 28 models are 2-D models, which only considered horizontal curve and vertical curve. According to a study intended to develop 3D (cross section, horizontal curve and vertical curve) models for operating speed prediction, the maximum difference between the observed and predicted speeds using 3-D model and 2-D model at some sites reached 35% (Gibreel et al, 2001). The 3D models have significantly higher values of coefficient of determination, indicating that the predicted operating speeds are in agreement with the observed values. In some of the studies shown in Appendix A, the number of observations per site was less than 100, with the lowest number observed at a site being 30 vehicles. Therefore, the accuracy of these models might be questionable. A few studies used radar gun as the data collection device. The utilization of radar gun is usually accompanied by possible human error and cosine error. It is possible that the presence of the speed collectors might influence drivers' behavior. In most of the studies regression models were developed based on the data collected and no validation was completed. Also almost all studies, provided the measurement-of-fit of their models without assessing the quality of prediction.

A recent study conducted in Norway and Sweden for estimating optimal speed limits compared four perspectives: societal, road user, taxpayer, and residential (Elvik, 2002). The study reported that the road user perspective and the taxpayer perspective resulted in the highest speed limits while the residential perspective was the lowest. According to the societal perspective, optimal speed limits were close to current speed limits in Norway, except on rural highways, where a reduction from 80 km/h to 70 km/h would be optimal. However in Sweden, the optimal speed limits based on the societal perspective were lower than the current speed limits in rural areas but were higher than current speed limits in urban areas.

For checking the consistency of design speed and operating speed on horizontal curves, three models were developed for two-lane rural highways based on the degree of curvature, length of curvature, deflection angles, and 85th percentile speed on approach tangent (Krammes et al., 1994, 1995). They are:

$V_{85} = 103.66 - 1.95D \quad (R^2 = 0.80)$
$V_{85} = 102.45 - 1.57D + 0.0037L - 0.10I \quad (R^2 = 0.82)$
$V_{85} = 41.62 - 1.29D + 0.0049L - 0.12I + 0.95V_t. \quad (R^2 = 0.90)$

Where: V_{85} = 85th percentile speed on the curve (kph); V_t = 85th percentile speed on approach tangent (kph); D = degree of curvature; L = length of curvature (m); and I = deflection angle (degrees).

McFadden and Elefteriadou (1997) used bootstrapping statistical method for developing models with same functions as the above three FHWA models. Bootstrapping involves splitting the existing database into two random samples where one half is used for model development and the other half for validation. Their models are:

$V_{85} = 104.61 - 1.90D \quad (R^2 = 0.74)$
$V_{85} = 103.13 - 1.58D + 0.0037L - 0.090I \quad (R^2 = 0.76)$
$V_{85} = 54.59 - 1.50D + 0.0006L - 0.12I + 0.81V_t. \quad (R^2 = 0.86)$
The notations for these models are the same as those presented above.

This aimed in examining and validating FHWA models. The study found that the models developed using the bootstrapping technique were statistically equivalent to the models developed in the FHWA study. Also, the comparison between predicted and actual speeds showed no significant differences between the observed and the model predicted 85th percentile speeds. The study concluded that bootstrapping technique is a very useful tool that can be used in many related areas of transportation field as it eliminates the need for collecting large quantities of data which is very typical for developing and validating empirical models.

There exists a strong correlation between speeds and roadway characteristics, hence operating speeds on curves and tangent sections can be predicted. Operating speeds on curves are governed by a limited number of parameters such as curvature, superelevation, and side-friction. This makes the prediction of operating speed on curves easier than on tangent sections. Also, due to insufficient database only a few studies have dealt with the problem of correlating the speeds with tangent road elements.

Polus et al. (2000) collected a large amount of data in six states from 1996 to 1997 and developed four models estimating operating speeds along tangent sections of two-lane rural highways. In these models both primary variables, such as preceding and succeeding radii of curves, length of tangent and secondary variables, such as presence of spirals, topography, average horizontal curvature and average slope were considered. To achieve the highest degree of reliability in predicting the 85th percentile speed on tangent sections, roadways were classified in to four groups based on curve radii and the length of the tangent between. The models are:

$SP = 101.11-3420/GM_S$	($R_1, R_2 \leq 250$ m, TL= 150 m)
$SP = 98.405-3184/GM_L$	($R_1, R_2 \leq 250$m, 150 m $\leq$ TL $\geq$ 1000 m)
$SP = 105.00-28.107/e\hat{}\,(000108 * GM_L)$	($R_1, R_2 \geq 250$ m, 150 m $\leq$ TL $\geq$ 1000 m)
$SP = 105-22.953/e\hat{}\,(0.000128 * GM_L)$	(R_1, R_2 at par with the minimum radius criterion for known or assumed design speed, TL $\geq$ 1000 m)

Where: SP = 85th percentile speed (kph); R_1, R_2 = previous and following curve radii (m); TL = tangent length (m); GM_L = geometric measure of tangent section and attached curves for long tangent lengths (m^2); and GM_S = geometric measure for short tangent lengths (m).

These models are valid for two-lane rural highways where the volume is rather low (fewer than 2,000 vehicles per day) and does not affect speed choice. The analysis showed that the first two models fit well. The other two models are preliminary and they clearly require additional data for both development and validation.

Jessen et al. (2001) developed equations to predict the 85th and 95th percentile speed at the point of limited sight distance on vertical curves and at control locations- locations where it is assumed that drivers are traveling at their desired speed. They collected operating speeds at 70 vertical crest curves located on rural two-lane highways in Nebraska. The equations are based on posted speed limit, approach tangent grade, and average daily traffic volume. Another approach of predicting operating speed is by the use of a series of regression equations on posted speed limit. This was developed by Fitzpatrick et al. (2003), and these equations assumed that speed limit is the only factor that determines the operating speed. For all roadways the general equation is:

$$EV85 = 7.675+0.98*PSL$$

Where: EV85 = estimated 85th percentile speed (mph); PSL = posted speed limit (mph)

They also developed a set of equations that could be used when the functional class of the roadway is known. These equations are:

EV85 = 8.666 + 0.963*PSL	Suburban/Urban Arterial
EV85 = 21.131 + 0.639*PSL	Suburban/Urban Collector
EV85 = 10.315 + 0.776*PSL	Suburban/Urban Local
EV85 = 36.453 + 0.517*PSL	Rural Arterial

Limited number of sites available for statistical analysis is the only limitation that might pose a problem while estimating 85th percentile free-flow operating speeds. Other variables that show some sign of influence on 85th percentile free-flow operating speed are access density, median type, parking along the street, and pedestrian activity level.

Enforcement is often required to assure that drivers adhere to speed limits. Past research showed that the presence of a police vehicle forced drivers to drive at speeds that are more compliant with speed limits (Shinar and Stiebel, 1986; Benekohal et al., 1992; Hauer et al., 1982). Aerial enforcement has been proven to be positive in reducing highway speeds but as observed by Saunders (1979), it showed negative results when it was deployed and removed. In a study carried out by Blackburn et al.(1989) aerial enforcement was found to be significantly more effective than radar in detecting and apprehending drivers, who used radar detectors and CB radio. Research by Teed and Lund (1991) found the use of laser guns to be more effective than radar guns in identifying speeding drivers. The use of cameras has also been proven to be an effective means of enforcing speeding laws. Rogerson et al. (1994) found that the crashes within 1 km of a speed camera have significantly reduced. Also within this area, a speed reduction greater than 15 km/h was observed. Freedman et al. (1993) found drone radar was related to a 1 mph reduction in average vehicle speed but Streff et al. (1995) reported little significance in speed reductions due to the drone radar deployment. Dart and Hunter (1976) evaluated the effects of speed indicator and they found that the speed indicator had no significant effect on operating speeds. On the contrary, Casey and Lund (1990) found that the presence of a speed indicator reduced traffic speeds at the placement sites and for a short distance past the site. Perrillo (1997) observed 2-3 mph reductions in the vicinity of the speed feedback trails in Texas. Public information and education played no significant role in the reduction of speed, speeding, crashes, and crash severity. Installation of several traffic enforcement signs has proved to result in safer driving habits and a significant reduction in the number of crashes that resulted in injury.

2.6 Summary

From the review, several important observations were made. The concept of using design speed as the main criterion for designing the various roadway elements leads to discrepancies among the design speed, operating speed and posted speed limits. Ideally, it is preferred to have the same or similar values for all the three speeds. However, in reality this is not the case. The design of roadway elements is primarily carried out by an assumed design speed. Research to date has reported that this assumption can be made on several factors that include legal speed limit, anticipated operating speed, terrain, accident history, functional classification and traffic volumes. However, in most cases the design speed does not match with the operating speeds, creating safety issues.

The studies reviewed here showed that the introduction of operating speed as a design criteria helps in getting closer to achieving the ideal situation of similar design and operating speed. Also the operating speed, when compared to the design speed, can be better approximated by using a feedback loop procedure. Hence, the use of operating speed measures into the traditional design speed concept should be considered for future inclusion in design policies.

Driver, environmental, vehicular and roadway characteristics govern the operating speed. Using these factors many models for predicting operating speeds along roadway segments were developed. Some studies have also attempted to relate operating speed with design speed. These models can be used to derive a relation between the anticipated operating speed and design speed and the consistency of the same can also be checked. However, these models reflected that the prediction of speeds on curves was easier than on tangent sections.

In essence, the speed limit of a roadway should be set at the 85^{th} percentile speeds. Most of the studies reviewed used 85^{th} percentile speed as the best indicator of operating speeds on any roadway section for a given set of roadway conditions. Hence, by posting speed limits within a range of 5 mph of the 85^{th} percentile speeds, potential discrepancies between operating speeds and posted speed limits are minimized. This also ensures a lesser dispersion of speeds. The result of this, as reported by some studies, is a reduced occurrence of crashes.

Several studies related to safety were reviewed to understand the effects of various forms of speed on crash rates. It was observed that a greater deviation from the mean travel speed resulted in a greater chance of crash occurrence. In short, greater speed variance results in a higher incidence of crashes. Also, change in speed at impact plays a vital role in changing an incident into fatality. Studies revealed that the change in posted speed limits on low and moderate speed roads have no significant effect on crash rates.

Under the current practices, the speed on a roadway section is regulated by posting speed limit signs. But mere posting of signs does not change the behavior of the driving public. Additional enforcement in the form of speed laws must be incorporated to ensure maximum compliance to speed limits. Various methods of enforcement include police patrol cars, aerial enforcement, laser guns, warning signs and vigilance cameras.

Numerous models on basis of geometric features for rural two-lane highways have been developed in the past decades to predict operating speed. Among the variables used for predicting operating speed, the radius of a curve is the most significant variable. Other significant variables include: length of the curve, length of the preceding and successive tangents, grades, superelevation, average daily traffic volume, pavement condition, approach speed, and speed limit.

3 METHODOLOGY

3.1 Data Collection

3.1.1 Site Selection

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 of the database 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
- In state geographic distribution

A total of 140 sites were selected for this study. There were 47 sites with design speed less than speed limit, and 93 sites with design speed greater than speed limit. The characteristics for these sites are summarized in Table 1.

Table 1: Features of Selected Sites

	Design speed > Speed limit		Design speed < Speed limit		
Highway	Rural	Urban	Rural	Urban	Total
2-lane	69	8	46	1	124
4-lane	4	11	0	0	15
6-lane	0	1	0	0	1
Total	73	20	46	1	140

The sites were distributed widely across Kentucky (Figure 2) and were selected from 64 of the 120 counties. Terrain covered all terrain types including level, rolling, and mountainous.

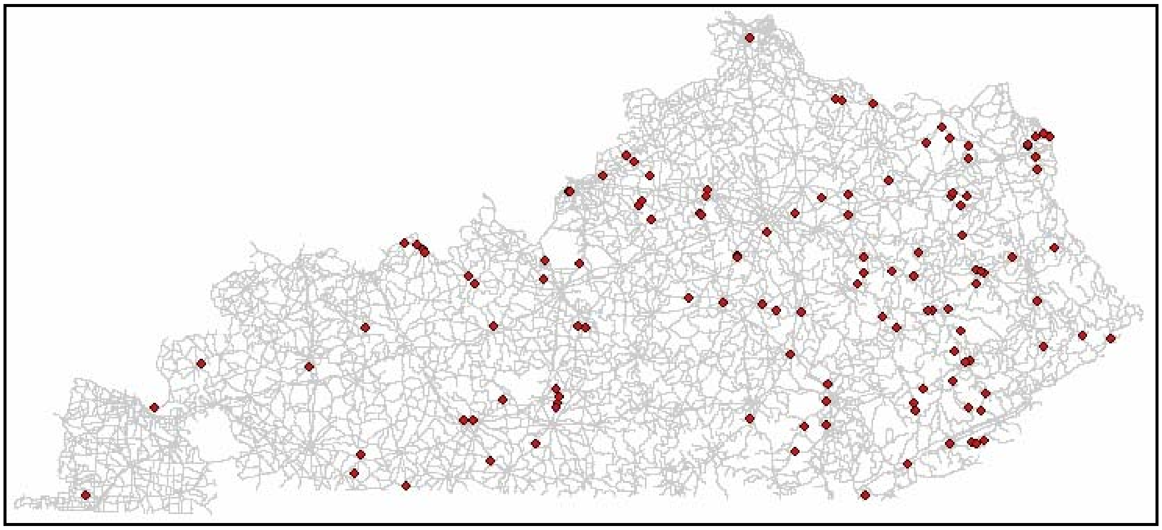


Figure 2: Geographic Distribution of Sites

3.1.2 Geometric Data

Using the site location information (county, road name, and mile point), the geometric data of each location were extracted from the Highway Performance Monitor System (HPMS) 2003 version. The extracted geometric data that were used to develop the database for analysis include: lane width, right shoulder width, and left shoulder width. Since most of these roads are rural two-lane highways, no median was present.

One of the important speed predictors from the literature review was the curve radius. In HPMS, a road has been separated into segments with the same geometric characteristics. Although the horizontal geometric data were also recorded in HPMS, there was no detailed data such as curve radius for each horizontal curve. Therefore the curve radii had to be estimated. In this study, Arc Geographic Information System (ArcGIS) and AutoCAD were used to measure the horizontal curve radii. The steps followed for this are the following:

1) Extract geometric information from HPMS to develop a database.
2) Use the Geographic Positioning System (GPS) data of the sites to develop another database.
3) Import these two databases and the shape file of the statewide roads to ArcGIS.
4) Mark the sites where speed data were collected in ArcGIS.
5) Export the marked sites and these roadway sections to AutoCAD.
6) Draw horizontal curves to simulate the real curves, and estimate the radius of the curve.
7) Measure the curve radii and the length of the curves through AutoCAD.

Design speed was obtained from HPMS and District Offices of the Transportation Cabinet. Speed limit was obtained from HPMS and verified onsite. Additional information was also obtained from HPMS including functional classification, number of lanes, median width, lane width, and shoulder width.

3.1.3 Speed Data Collection

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.

3.2 Data Analysis

3.2.1 Data Reduction

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. The data information for each site used is presented in Appendix B.

3.3 Operating Speed Prediction Model Development

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. The model development procedure is shown as Figure 3.

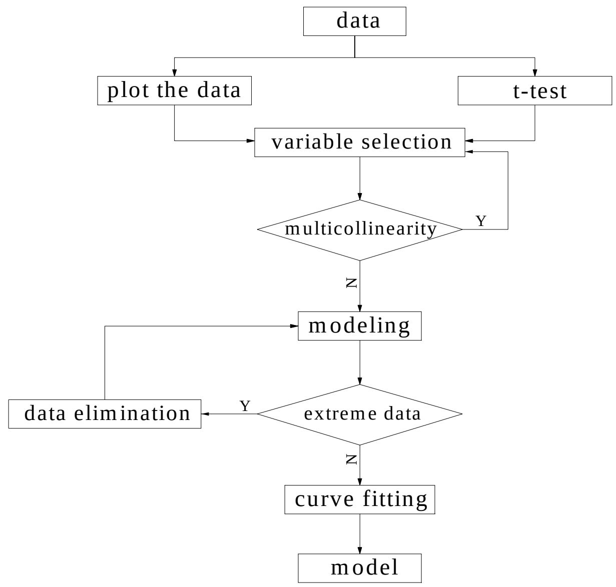


Figure 3: Model Development Procedure

Scatter plot was used to identify possible relationships between the independent variables and the 85th percentile speed. Using the available variables, possible regression models were developed. A more detailed description of the approach used is presented in Appendix C.

3.4 Safety Analysis

Another element of concern is whether the speed inconsistencies have any safety effect on these roadways. A two step analysis was performed to evaluate this issue:

1. Crash rate analysis: This approach 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.
2. Crash prediction models: This approach aims to develop a predictive model for determining the impact of design choices on crashes.

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.

For the second approach, the same modeling processes as noted in the previous section will be utilized. Therefore, regression models will be developed and evaluated that will allow for determining the most appropriate variables that could predict the safety performance of a section. The models will evaluate as dependent variables the number of crashes and the crash rates. Each alternative will be modeled and the most appropriate model will be selected. For the models of the crash numbers, the relative exposure (measured as the product of volume and length) will be used as an offset variable.

The models to be developed here utilize extended negative binomial regression analysis. This approach allows for decomposing the roadway segment into subsegments within which each characteristic used remains constant. In, general, crashes are considered random events while traffic volumes are more predictable and less random than crashes. Therefore, assuming that crash rates are the number of crashes divided by exposure (product of traffic volume and section length), then a prediction model for crash rates can be formulated as follows:

$$\text{Log (CR)} = b_0 + b_1X_1 + b_2X_2 + \ldots + b_kX_k$$

where CR is the crash rate, b_i the model coefficient, and X_i the model predictors. Assuming that CR = C/EXPO where C the number of crashes and EXPO the exposure, then the above equation becomes

$$\text{Log (C)} = b_0 + b_1X_1 + b_2X_2 + \ldots + b_kX_k + \log(\text{EXPO})$$

The last part is the offset variable that is used in the model. Current research on safety modeling uses this approach and thus, it was considered appropriate to use it here for the development of crash prediction models.

Generalized linear models are used to identify the most appropriate variables that could predict the crashes using the negative binomial distribution. The SAS procedure *genmode* is used for this and the models are evaluated based on the model's dispersion and deviance, where both should be close to 1.00.

4 DATA ANALYSIS AND RESULTS

4.1 Design Elements and Speeds

The first step in the data analysis was the examination and identification of potential trends that are present. A number of design elements were examined in relation to the design speed used and the operating speeds observed in the field. These elements included the radius and length of the curve, the lane and shoulder width, and the median width (when present).

The sites examined were rural 2-lane and 4-lane highways. First, these trends 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 operating speed prediction models were developed for 2-lane roads. All 4-lane roadways had a design speed greater than the posted speed limit. In summary, the trends 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. These trends are discussed in the following sections.

4.1.1 Design Speed Trends

There were eight design characteristics that were examined in this step and each one is briefly discussed here. A more detailed discussion for each of the three groups examined here is presented in Appendix D. Traditionally, design speed has been selected to determine the minimum radii of horizontal curves for a roadway section. The general rule is that greater design speeds allow for larger curve radii and the data used here supports this assumption. The trend between design speed and length of horizontal curve was also examined showing that **Error! Reference source not found.**shorter horizontal curves had lower design speeds. The trends for these two curve design elements indicate that the choice of the radius and subsequently the length of the curve are dependent of the design speed selected. The data for the right shoulder width indicates that roads with higher design speeds had wider right shoulder; an expected pattern. The data for the lane width did not show any trend, indicating that the choice for the lane width is somewhat independent from the design speed selected and is more likely affected by other factors such as terrain, right of way restrictions, design vehicle, and costs. The trends for the speed limit showed in general an agreement between design speed and speed limit with higher speed limits for greater design speeds. A trend was observed for the AADT, where higher volumes resulted in greater design speeds.

The various relationships and trends between design speed and geometric elements are summarized in

Table 2. The data for the 2-lane highways showed that there are some relationships between design speed and various geometric elements. Most of them seem to follow the general assumption that greater design speeds lead to larger values for the elements selected. On 2-lane highways where the design speed was lower than the posted speed limit these relationships were absent indicating that the choice of design speed does not impact the value chosen for the element. It could be assumed that these values are affected more by other parameters, such as terrain, location, and roadway context. For the other two sets and in general, the typical

relationship of correspondence between design speed and element values was noted. The speed limits in general followed a similar trend to the design speed, with higher speed limits corresponding to greater design speeds. The trends for AADT showed a corresponding trend for 2-lane roads and for 2-lane roads design speeds greater than the speed limits. The other sets showed a surprising and unexplainable opposite trend where lower design speeds were utilized for larger volumes.

Table 2: Summary of design speed and geometric design elements

Element	Highway			
	2-lane	2-lane D<L	2-lane D>L	4-lane
Radius	+	o	+	+
Length of curve	+	-	+	-
Lane width	o	o	+	-
Median width	NA	NA	NA	+
Right shoulder width	+	o	+	+
Left shoulder width	NA	NA	NA	+
Roadway width	+	o	+	+
Speed limit	o	+	+	+
AADT	+	-	+	-

Notes: + element changes in the same direction as design speed changes;
- element changes in opposite direction as design speed changes;
o no effect between design speed and element;
NA not applicable

4.1.2 Operating Speed vs. Geometric Features

A similar analysis was undertaken for the determination of the trends for the operating speeds. The summary is presented here while the detailed discussion is included in Appendix D. Operating speeds increased as curve radius and length of horizontal curve increased. Lane width, right shoulder width, and road width are also features of concern that could have an impact on operating speed. On sites with wider lane and right shoulder (as well as roads wider roads), higher operating speeds were observed. It should be pointed out that, lower operating speeds were observed on sites with narrower lane and right shoulder. The trend for design speeds showed that there is an agreement between these two speed metrics with higher operating speeds on roadways with greater design speeds. The speed limit trends also showed the same corresponding relationship.

The various relationships and trends between operating speed and geometric elements are summarized in **Error! Reference source not found.**. The data for all roadways showed that greater values resulted in higher operating speeds. This trend was apparent for all types of highways indicating that drivers translate the larger values as conducive to speeding. This behavior has the potential to misinterpret the roadway designs and thus create safety problems.

Table 3: Summary of operating speed and geometric design elements

Element	Highway			
	2-lane	2-lane D<L	2-lane D>L	4-lane
Radius	+	+	+	+
Length of curve	+	+	+	+
Lane width	+	+	+	+
Median width	NA	NA	NA	+
Right shoulder width	+	+	+	+
Left shoulder width	NA	NA	NA	+
Roadway width	+	+	+	+
Design speed	+	+	+	+
Speed limit	+	+	+	+

Notes: + element changes in the same direction as design speed changes;
- element changes in opposite direction as design speed changes;
o no effect between design speed and element;
NA not applicable

4.2 Design Speed, Operating Speed, and Posted Speed Limit Relationships

To determine the relationships between any two of these speeds[1], the data was used in similar groupings as before. In addition to the four sets utilized up to this point, a new group is considered here. This new group consisted of a set of special sites identified as areas with a design speed greater than speed limit and it consisted of sites that were of special interest to the SAC. These sites were predominantly curb and gutter sections with a two-way left-turn lane (TWLTL) (14 sites), with nine sites with TWLT only, seven sites with curb and gutter only, and four sites with neither. These 34 sites were examined independently of the other sites, since they were representing longer segments and not always contained a horizontal curve (as it was the case in the other sites).

4.2.1 Operating Speed vs. Design 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

[1] These relationships were examined using a paired t-test and ensuring normality of the distribution. Details on each comparison are presented in Appendix E along with statistical results.

agreement between operating and design speeds.

4.2.2 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 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.

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.

4.3 Safety Analysis

4.3.1 Crash Rates

The first 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. The detailed crash data for the sections are shown in Appendix F.

<u>4.3.1.1 2-Lane Rural Highways, Design Speed Lower than Speed Limit</u>

Among the 37 sites used here, 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.

4.3.1.2 2-Lane Rural Highways, Design Speed Greater than Speed Limit

There were 67 sites that were used in this 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.

4.3.1.3 4-Lane Rural Highways

There were 13 sites that were 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.

4.4 Special Sites

The set of special sites identified by the SAC were further examined to determine whether any operational and safety trends were apparent regarding the presence of curb and gutter and/or two-way left-turn lanes. For each of these elements, distinct issues are present that warrant such an additional evaluation. Medians are considered beneficial in reducing crashes but there is a concern that high design speeds and, possibly, posted speed limits may diminish their positive impact. This concern may be more valid for flush medians including two-way left-turn lanes.

Curb and gutter design has been used in the past as means to reduce design speed and roadway width. Recent studies have indicated that the presence of curb and gutter does not have any significant effect in moderating operating speeds, since the drivers rarely associate them as a speed reducing indicator.

A total of 24 sites were identified by SAC members aiming to address these issues. There were 11 sites where a TWLTL was present, 5 sites where curb and gutter was used, 5 sites where both TWLTL and curb and gutter were present and 4 sites that had neither. Speed limits were either 45 or 55 mph and most of these roads (17 segments) were 4 lane facilities. The design speeds for these sections were originally obtained from the HPMS data and verified by the District Offices. However, there were few segments that the design speeds were not verified and they seem to be relatively high for the design features of the roadway. All but three curb and gutter sections have a design speed of 60 or 70 mph, which may indicate an error in the HPMS data.

4.4.1 Operational Characteristics

There were only four sites among those with curb and gutter where the operating speed was greater than the design speed. The opposite was true for the remaining sites: the design speed was greater than the operating speed. The difference between operating speed and posted speed limit was also examined and indicated that for all these sites but two the operating speeds were greater than the posted speed limits. This finding is in agreement with prior research findings indicating that curb and gutter has little effect on operating speeds. The magnitude of both differences (operating speed minus design speed and operating speed minus posted speed limit) ranged significantly from -15.5 mph to 11.5 mph. An attempt to identify potential correlations with any other elements, such as AADT, number of lanes, and lane width, did not produce any reasonable relationships. It should be noted that relatively large differences were noted between design speed and posted speed limit for most of these sections which may contribute in the discrepancies between operating and design speeds. The reliability of the design speed data is also questioned and therefore some of these large differences may be indeed smaller.

There were five sites among those with TWLTL where the operating speed was greater than the design speed. The difference between operating speed and posted speed limit showed six sites where the posted speed limit was greater than the operating speeds. These six sites had a posted speed limit of 55 mph, four were two-way roads, five had 12-foot lanes, and varied shoulder width and AADT. It should be noted though that the differences were small (all less than 5 mph and two sites with differences less than 1 mph) and therefore may be of no significance. Given the small differences in operating speed and posted speed limit, it was deemed that no significant operational issues are associated with these sites. A similar attempt to correlate any of the other elements to the differences in speeds did not provide any additional insight. Again large differences between posted speed limit and design speed were observed for these segments which are likely the contributing factor in the discrepancies between operating speeds and posted speed limits.

An examination of the effect of the curb and gutter on the operating speeds was undertaken by comparing the average speed of these sections to sections with some shoulder (either full or partial). The results are summarized in Table 4. These data indicate that, in general, the operating speeds in curb and gutter sections are lower than the comparable sections with shoulders. This observation however was not valid for 4 lane roads with a 55 mph posted speed limit, indicating that operating speeds are slightly greater in the curb and gutter sections. This may be indicative of the smaller influence that curb and gutter has on 4-lane, high speed facilities, since a significant difference is noted for the 45 mph speed limit 4-lane roads. It is apparent that this difference is mostly attributed to the number of lanes, since it does not hold for 2-lane roads. An interesting observation here is the similarity of operating speeds in 4-lane roads with shoulders for both 45 and 55 mph speed segments. This could be interpreted as an influence of the cross section dimensions rather than the speed limit. Finally, the difference for the curb and gutter sections between operating speed and posted speed limit is smaller for the 55 mph roads than the 45 mph. This could be considered as an indication of the reduced effectiveness of curb and gutter for these roadways and the greater influence of the number of lanes and other cross section elements on the divers' operating speed.

Table 4 Operating speeds for segments with curb and gutter vs. segments with shoulders

Speed Limit	Number of lanes			
	2 Lanes		4 Lanes	
	C & G	Shoulder	C+G	Shoulder
45	56.80	NA	52.45	57.50
55	54.50	56.00	58.23	57.94

4.4.2 Safety Analysis

First, all sites were examined to determine whether there were any general safety issues among the sites. There were 30 sites that were used in this analysis and only three were considered spots. Among the 27 segments, there were 4 that had no crashes and the remaining had crash rates ranging from 0.3 to 289.9 crashes per 100 MVMT. Among the three spots, one had no crashes and the other two had a rate of 0.3 crashes per million VMT. The Critical Rate Factors show that there was only one segment with rate slightly greater than 1.00, which was 1.05 and could be considered as of no significance. Given this observation, it was determined that there are no specific safety issues at these locations, since they do not exhibit a different pattern compared to similar roads in Kentucky. Similar results were noted for the analysis of the injury only crashes as well as the speed only related crashes. The same trends and conclusions were drawn from the individual examination of each subgroup. Therefore, there are no special safety concerns for these sites.

4.5 Speed and Safety Models

One of the objectives of this study is to examine and develop relationships for operating speeds, design speed and speed limits. In general, posted speed limits are greater or lower than design speeds. In this study, the sites were partitioned based upon the relationship between posted speed limit and design speed.

Most of the sites were rural 2-lane and 4-lane highways. To understand the relationships between operating speed and highway geometric features, operating speed prediction models were developed. First, a model was developed 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 operating speed prediction models were developed for 2-lane roads. All 4-lane roadways had a design speed greater than the posted speed limit, and thus only this model was developed for these roads. In summary, 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. The development procedures for each of these models are presented next.

Each model was developed based upon the development procedure presented earlier (Figure 3). The best variables capable of predicting operating speed were selected from among all possible variables. These variables 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.

4.5.1 2-Lane Rural Highways

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:

$$V_{85} = 26.903 + 0.495\, DS + 0.003\, LC - 0.437\, DL - \frac{1633.641}{R}$$

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.

4.5.2 2-Lane Rural Highways, 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:

$$V_{85} = 56.914 - \frac{3883.586}{R}$$

Where V_{85} = 85th percentile speed (mph) and R = radius of curve (feet). The model’s R^2 is 0.4398.

4.5.3 2-Lane 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:

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

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.

4.5.4 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.

4.5.5 Crash Models

The next analysis focused on the development of prediction models and the documentation of potential factors that could contribute to a crash occurrence. One of the variables closely examined here is the difference between design and operating speeds. The assumption is that there is potential influence on the crash history of these sections that could be attributed to these very differences and possibly their range. The models developed examined as dependent variable the number of crashes using the crash exposure (vehicle miles of travel for each section) as an offset variable. The only models that produced some reasonable results were for 2-lane rural highways and their subset of roads with design speed greater than speed limit.

4.5.5.1 2-Lane Rural Highways

All 103 sites were used for this analysis. The only variable that was statistically significant is the right shoulder width. The model form is

$$C = EXPO\ e^{1.530 - 0.139\ RSW}$$

Where C = crashes per year; EXPO = ADT x section length x 365 x 10^{-6}; RSW = right shoulder width. The model had a deviance of 0.66 and a dispersion factor of 0.838, resulting in a reasonable model.

The right shoulder width coefficient could be used to predict the relative change in the number of crashes by change the variable by one unit, i.e. 1 foot. This is computed as the exponent of the coefficient: $e^{-0.139} = 0.87$. This implies that an increase in shoulder width by 1 foot will result in 0.87 times fewer crashes, assuming that the exposure remains the same.

4.5.5.2 2-Lane Rural Highways, Design Speed Greater than Speed Limit

There were 67 sites used for this analysis. The only variable that was statistically significant is also the right shoulder width. The model form is

$$C = EXPO\ e^{1.776 - 0.180\ RSW}$$

Where C = crashes per year; EXPO = ADT x section length x 365 x 10^{-6}; RSW = right shoulder width. The model had a deviance of 0.82 and a dispersion factor of 0.799, resulting in a reasonable model.

The right shoulder width coefficient could be used to predict the relative change in the number of crashes by change the variable by one unit, i.e. 1 foot. This is computed as the exponent of the coefficient: $e^{-0.139} = 0.84$. This implies that an increase in shoulder width by 1 foot will result in 0.84 times fewer crashes, assuming that the exposure remains the same.

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

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. A fourth set of data was also collected on roadways specifically identified as potentially problematic by the SAC due to disparities between design speed and posted speed limit and the presence of two-way left-turn lanes at high speed facilities. Speed data and roadway geometry data were collected along these sites to allow for the development of the appropriate evaluation.

First, the trends of the various geometric features identified were examined in relation to the design and operating speeds of the sections. The next 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. Special emphasis was placed on the sections recommended by SAC to determine possible operational and safety issues that may arise from the continuance of designing and constructing such sections. Finally, operational and safety models were developed to allow for the prediction of the 85th percentile operating speed and number of crashes based on the values of the selected design elements.

The trend analysis for the design speed showed that there are some relationships between design speed and the various geometric elements. For most of these elements, the general assumption that greater design speeds lead to larger values for the elements selected seems to hold. For roadways where the design speed was lower than the posted speed limit there was no apparent trend for any of these elements and for almost all elements there was no relationship between the values used and design speeds. It could be assumed that these values are affected more by other parameters, such as terrain, location, and roadway context. The speed limits in general followed a similar trend to the design speed, with higher speed limits corresponding to greater design speeds.

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 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. In general, the relationship between operating speeds and posted speed limit held true for these sections as it was the case from previous studies.

Similar conclusions regarding the discrepancies among speeds could be drawn for the special sections recommended for evaluation by the SAC. Roadway sections with curb and gutter showed that, in general, the design speed was greater than the operating speed and the operating speeds were greater than the posted speed limits. The segments with TWLTL exhibited similar trends as well but the differences were smaller than those observed for the curb and gutter sections. Large differences between posted speed limit and design speed were observed for both roadway types which are likely the contributing factor in the discrepancies among these speed metrics. The fact that the design speed may still be not reliable may have an effect on these observations.

The influence of curb and gutter on these segments was present for 2-lane and for 4-lane facilities with a 45 mph speed limit. This could be an indication of the effectiveness of curb and gutter sections on these roadways. However, this influence was not noted on 4-lane roads with 55 mph speed limit, indicating that other features than the curb and gutter are influencing operating speeds. Operating speeds in 4-lane sections with 45 mph speed limit were 7.5 mph above the speed limit, while for 55 mph speed limit the difference was only 3.2 mph. Therefore, the presence of the curb and gutter on these roadways had a small effect on impacting operating speeds.

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. The sections in the special sites (curb and gutter and TWLTL sections) had no sections with critical rates greater than 1.00 indicating that the speed inconsistencies do not lead in general to safety problems. It should be noted though, that this findings 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 performed before extending the use of these models.

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 between 30 and 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.

The crash prediction models developed here identified some elements that have a predictive power. For 2-lane roadways, the right shoulder width showed a contribution to crashes. For the subset of 2-lane roads with design speed greater than the speed limit, the shoulder width was also identified as significant crash predictor. For the other roadway types examined no significant models could be developed. These findings indicate that there are elements that could influence the crash occurrence and they should be considered in determining the values to be used. Moreover, these models provide an additional support for considering more carefully the choices made when selecting the design speed and the various dimensions of the design elements.

An interesting element identified in the relationships between speeds and geometric features as well as safety and geometric features is the presence of the right shoulder width. This geometric element was a significant variable in the speed prediction models as well as in the crash prediction models. This finding underscores the importance of this element both in assisting the driver to select the appropriate operating speed as well as in impacting roadway safety. However, the paradox is that wider shoulders will increase operating speeds (coefficients are greater than 1 indicating increase of speed with larger shoulder widths) and reduce crashes (coefficient is negative indicating increase will reduce crashes). This 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.

5.2 Recommendations

The objective of this work was to first answer the basic concerns posed by the SAC and then 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 specific elements of particular attention as expressed by the SAC are summarized here along with recommendations as they result from the analysis presented here.

1. *Are there any safety and liability concerns when speed limits exceed design speeds?*
   The safety analysis indicated that the sites examined did not exhibit any safety issues and very few had crash rates greater than the critical crash rates. Therefore, at this point no specific safety concerns are present. As noted in the previous section, the fact that these segments did not indicate any problems is not a basis for continuing this practice. It is recommended that a better process be developed and followed when selecting design speeds that could actually reduce and possibly eliminate such disparities between design speed and posted speed limits.

2. *When and where should curb and gutter sections be used as related to design speed and safety?*
   The analysis of the sites proposed by the members of the SAC did not allow for developing a complete identification of possible locations and geometric features that could have a significant influence on the operational and safety performance of these sites. It is apparent that the use of such a design does not have any effect on operating speeds; on the contrary operating speeds were in general higher than the posted speed limits. These sections did not pose any safety concerns by demonstrating crash rates lower than the critical rates. Based on these observations, it is recommended that curb and gutter sections be closely examined and their applicability should be considered based on the context of the roadway. Other measures that may have a stronger influence on operating speeds may be considered in conjunction with curb and gutter design, if the intention is to affect operating speeds and to minimize the differences between operating speed and posted speed limits.

3. *Should flush medians be used for speeds greater than 45 mph?*
   The segments provided did answer this question indirectly by assuming that a TWLTL is a flush median. The analysis showed once more that there is no operational or safety issues with any of the sections analyzed here. All but 3 sections had a speed limit of 55 mph, which may be considered as an indication that this practice could be continued. It should be also pointed out that the differences between operating and design speeds were relatively large denoting an inconsistency in design. The use of two-way left-turn lanes in high speed facilities could be continued but it is recommended that a more thorough evaluation should be conducted.

4. *What are the concerns when the operating speed is greater than the speed limit?*
   Most of the segments (two-lane, four-lane and special sites) analyzed here showed that operating speed is, in general, higher than the posted speed limit. The major concern of this trend is the pitfall that if a speed study is conducted, then the posted speed limit could be raised since the 85^{th} percentile speed will be higher which in turn will lead to great disparity between the design and operating speeds. Therefore, the roadway context and the desired operating speed should be closely evaluated and determined from the outset to allow for avoiding such a scenario. 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.

The answers and recommendations to these questions point to a revision of the way that the design speed is selected. 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.

Based on the findings discussed in the preceding sections the following points are recommended as good design practice:

1. The selected design speed should be chosen based on the desired 85th percentile operating speed. This will reduce any disparity between these two speeds as well as between design speed and posted speed limit. Moreover, agreement between these two speeds will eliminate sites where design speed was lower than posted speed limit.

2. Curb and gutter alternatives should be closely examined and their applicability should be considered based on the context of the roadway. The determination of the actual reason for using such sections plays an important role in their placement. If the intention is to moderate speeds, then other measures that may have a stronger influence on operating speeds may be considered in conjunction with curb and gutter design.

3. The use of two-way left-turn lanes in high speed facilities could be continued but it is recommended that a more thorough evaluation should be conducted. This will allow for avoiding disparities between operating speeds and posted speed limits.

4. Models were developed for predicting the 85th percentile speed for 2- and 4-lane highways. The models are

$$V_{85} = 26.903 + 0.495\,DS + 0.003\,LC - 0.437\,DL - \frac{1633.641}{R} \qquad \textit{2-lanes}$$

$$V_{85} = 39.295 + 0.203\,DS + 1.024 * RSW - \frac{2949.627}{R} \qquad \textit{2-lanes, Design > Limit}$$

$$V_{85} = 46.357 + 1.153 * RSW \qquad \textit{4-lanes}$$

   where V_{85} = the 85th percentile speed (mph); DS = design speed (mph); LC = length of curve (ft); DS = design speed (mph); DL = design speed minus posted speed limit (mph); RSW = Right shoulder width (ft); and R = radius of curve (ft). The limitations of these models as described in the previous section should be also considered when they are used.

   Once a design is developed, its operating speed could be predicted using these models to examine whether the geometric features can provide the desired operating speed. If not, geometric features should be adjusted so that the desired operating speed can be achieved.

5. Current designer practices tend to result in a design speed selected in order to address the most restrictive geometric elements like horizontal curves, while ignoring the relationships between design speed and other elements, such as shoulder width. On the highways examined here, other elements showed that they have an impact on operating speeds. Therefore, ignoring these elements and their influence on operating speeds may lead to greater disparity between operating speed and design speed and thus result in greater inconsistency.

6. The safety analysis for the values of the geometric elements examined here indicated that there is influence of the shoulder width on the crash rates. The presence of this element in the operating speed prediction models underscores its importance and indicates that a more careful examination and decision on the value used is required.

7. The models predicted here for 4-lane rural highways are based on a small sample. It is therefore recommended that additional data is collected and further work is completed to properly evaluate such roadway designs and develop more appropriate models for these sections.

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APPENDIX A

SUMMARY OF PAST MODELS

Author	**Predictors**	**Data collection**	**Sample size**	**Maximum coefficient of determination**
Taragin	R	N/A	68(125)	0.86
Mclean	R, CCR	N/A	N/A	0.87
Mclean	R, V_F	N/A	120(N/A)	0.92
Kerman et al	R, V_a	N/A	N/A	0.91
Guidelines for the design of roads	CCR, LW	N/A	N/A	0.79
Glennon et al	R	N/A	N/A	0.84
Setra	CCR, LW	N/A	N/A	0.846
lamm and Choueiri	CCR, R, LW.SW	Stop watch	261(N/A)	0.842
Kanellaidis et al	R, V_d	N/A	58(200)	0.925
Lamm	CCR	N/A	N/A	0.73
Ottesen and Krammes	CCR,R	N/A	N/A	0.8
Morrall and Talarico	DC	Radar gun	9(N/A)	0.99
Islam and Seneviratne	DC	Video camera, radar gun	8(125)	0.98
Krammes et al	DC, L_c, DF, L, V_T	Radar gun	284(50~100)	0.9
Lamm et al	CCR	N/A	N/A	0.81
Choueiri et al	CCR	N/A	N/A	0.81
Al-Masaeid et al	DC, P_{con}, G, $R_1, R_2, L_{t,} DF_1, DF_2$	40 m speed trap	93(N/A)	0.81
Voigt	R	N/A	N/A	0.84
Abdelwahab et al	DC, DF	Stop watch	46(35)	0.92
Pasetti and Fambro	R	Counter/classifier	51(100)	0.68
Fitzpatrick et al	R, K, G	Radar & Lidar gun, counter/classifier	176(100)	0.92
Pottesen and Krammes	DC, L_c	Radar gun	216(50)	0.81
Andueza	R, R_a, DC, L_T	Radar gun	39(30~64)	0.85
McFadden and Elefteriadou	V_{85T}, L_T, R	Lidar gun	21(75)	0.712
Gibreel et al	R, L_V, G_1, G_2, A, L_0 e, K, DF	Radar gun	38(1h)	0.98
Jessen et al	V_P, G_1, ADT	Counter/classifier	70(275)	0.613
Donnell et al	$R, G_1, G_2, L_{T1}, L_{T2}$	Lidar gun	17(100)	0.611
Misaghi and Hassan	R, G, e, V_t, DFC SW,curve-dir, drv-flag	Counter/classifier	20(24h)	0.889

Note: Sample size is number of sites and number of observations per site respectively.
N/A= information was not provided.
A description of the predictors is also available.

Notation of the predictors shown next.

A = algebraic difference of vertical grades (%)
ADT = average daily traffic (vehicles/day)
CCR = curvature change rate (degree/km)
DC = degree of curvature (degrees)
DF = deflection angle (degrees)
DF1 = deflection angle for curves 1 of compound curve, (degrees)
DF2 = deflection angle for curves 2 of compound curve, (degrees)
DFC = deflection angle of circular curve (degrees)
Drv-flag = driveway flag (intersection on curve: drv-flag=1; otherwise: drv-flag=0
E = superelevation rate (%)
G = vertical grade (%)
G1 = first grade in direction of travel (%)
G2 = second grade in direction of travel (%)
Int-flag = intersection flag (intersection on curve: int-flag=1; otherwise: int-flag=0)
K = length of vertical curve for 1% change in grade (m)
L_C = length of horizontal circular curve (m)
L_T = length of tangent (m)
L_{T1} = length of preceding tangent (m)
L_{T2} = length of succeeding tangent (m)
L_V = length of vertical curve (m)
L_0 = distance between horizontal and vertical points of intersection (m)
LW = lane width (m)
P_{con} = pavement condition (PSR>=3: P_{con} =0; otherwise: P_{con} =0)
Pre-radius = preceding curve radius
R = radius of the curve (m)
R_a = radius of previous curve (m)
R_1 = radius of curve 1 of the compound curve (m)
R_2 = radius of curve 2 of the compound curve (m)
Sp-flag = spiral flag (curve with spiral: sp-flag=1; otherwise: sp-flag=0)
SW = shoulder width (m)
V_a = curve approach speed (km/h)
V_d = desired speed (km/h)
V_F = approach tangent speed (km/h)
V_P = post speed limit (km/h)
V_T = approach tangent speed (km/h)

APPENDIX B

SUMMARY OF SITE INFORMATION

Site	Operating Speed (mph)	Functional Class	AADT	Design Speed (mph)	Speed Limit (mph)	Lane Width (ft)	Right Shoulder Width (ft)	Left Shoulder Width (ft)	Radius (ft)	Length of Curve (ft)	Number of Lanes	Road Width (ft)
1	43.00	Major Collector	414	45	55	9	2	0	185	79.4	2	22
2	65.00	Minor Arterial	1220	50	55	9	1	0	5735	2982.77	2	20
3	63.00	Minor Arterial	1220	50	55	9	1	0	290	281.63	2	20
4	37.00	Major Collector	1770	40	45	9	2	0	300	124.2	2	22
5	55.00	Major Collector	540	50	55	9	2	0	725	702.89	2	22
6	51.00	Major Collector	3840	40	55	10	2	0	1415	783.83	2	24
7	41.00	Major Collector	1828	50	55	9	2	0	425	229.93	2	22
8	45.00	Major Collector	2883	50	55	10	2	0	570	192.07	2	24
9	50.00	Major Collector	737	45	55	9	2	0	540	425.21	2	22
10	60.00	Major Collector	517	50	55	9	1	0	1115	630.74	2	20
11	57.00	Major Collector	594	40	55	11	2	0	1540	750.66	2	26
12	45.00	Major Collector	1465	45	55	9	2	0	1935	988.38	2	22
13	42.65	Major Collector	414	45	55	9	2	0	95	115.55	2	22
14	38.00	Major Collector	682	50	55	10	2	0	260	243.24	2	24
15	54.00	Major Collector	667	50	55	9	2	0	495	462.73	2	22
16	40.00	Major Collector	687	40	55	9	1	0	500	303.12	2	20
17	59.40	Major Collector	3330	40	55	12	2	0	2810	2265.12	2	28
18	54.00	Major Collector	622	50	55	10	1	0	835	679.29	2	22
19	56.00	Major Collector	928	40	55	10	2	0	635	413	2	24
20	47.00	Major Collector	1470	45	55	9	1	0	405	322.18	2	20
21	42.15	Major Collector	593	40	55	10	2	0	395	176.99	2	24
22	44.00	Major Collector	708	30	35	9	2	0	290	240.01	2	22
23	49.00	Minor Arterial	6751	30	45	11	4	0	3995	2645.42	2	30
24	56.85	Minor Arterial	2159	50	55	9	2	0	715	512.43	2	22
25	48.00	Major Collector	1429	40	55	10	2	0	345	458.48	2	24
26	51.00	Major	744	50	55	12	6	0	2850	1234.35	2	36

		Collector										
27	54.00	Major Collector	2625	35	45	9	2	0	1205	735.9	2	22
28	57.50	Major Collector	603	35	55	9	2	0	675	472.71	2	22
29	52.00	Major Collector	2937	50	55	10	4	0	945	232.46	2	28
30	51.00	Major Collector	1413	40	45	9	2	0	545	559.55	2	22
31	56.40	Major Collector	2026	35	45	10	2	0	720	428.59	2	24
32	61.00	Minor Arterial	2731	45	55	10	2	0	235	257.38	2	24
33	48.00	Minor Arterial	2399	40	55	11	4	0	425	690.67	2	30
34	47.00	Major Collector	2600	35	55	11	2	0	320	194.88	2	26
35	51.00	Major Collector	2600	50	55	11	2	0	305	221.26	2	26
36	56.00	Major Collector	881	45	55	10	3	0	680	382.96	2	26
37	57.40	Major Collector	1055	40	45	9	2	0	595	754.88	2	22
38	59.00	Minor Arterial	4490	40	55	10	4	0	1165	420.45	2	28
39	57.00	Principal Arterial-Other	3537	50	55	11	1	0	705	588.8	2	24
40	57.00	Minor Arterial	1845	45	55	12	10	0	1935	2197.13	2	44
41	60.65	Principal Arterial-Other	11134	70	55	12	10	10	1580	882.37	4	165
42	42.00	Principal Arterial-Other	8205	70	35	10	2	0	295	193.56	2	24
43	44.00	Principal Arterial-Other	37366	45	35	12	0	0	1825	1731.75	4	74
44	51.00	Major Collector	3154	50	45	10	2	0	1850	414.31	2	24
45	38.00	Major Collector	1421	45	35	9	3	0	330	133.12	2	24
46	44.00	Principal Arterial-Other	1432	45	35	10	4	0	185	138.21	2	28
47	49.15	Principal Arterial-Other	1690	45	40	11	4	0	475	489.06	2	30
48	42.15	Minor Arterial	1210	50	35	10	2	0	775	205.86	2	24
49	62.15	Minor Arterial	8920	65	55	12	10	0	760	649.50	2	44
50	42.15	Minor Arterial	3320	50	35	10	1	0	585	169.26	2	22
51	47.15	Major Collector	529	60	55	9	1	0	745	290.09	2	20

52	40.15	Major Collector	743	60	55	10	2	0	475	906.99	2	24
53	40.15	Principal Arterial-Other	5784	62	55	10	3	0	755	500.27	2	26
54	52.00	Major Collector	4083	60	55	10	4	0	500	291.53	2	28
55	48.15	Principal Arterial-Other	16400	60	55	12	10	3	1280	1124.38	4	108
56	57.00	Major Collector	5168	60	55	12	10	3	1015	1052.40	4	88
57	56.00	Major Collector	2587	60	55	11	3	0	1085	266.09	2	28
58	50.00	Major Collector	654	50	45	9	3	0	725	374.05	2	24
59	56.00	Major Collector	4254	60	55	9	2	0	680	341.30	2	22
60	60.00	Major Collector	4254	60	55	9	2	0	2065	688.29	2	22
61	60.00	Principal Arterial-Other	15100	50	45	12	10	2	800	1593.78	4	67
62	57.00	Principal Arterial-Other	21430	55	45	12	10	6	2265	2926.20	4	88
63	53.00	Minor Arterial	11314	60	35	9	2	0	970	790.28	2	22
64	53.00	Major Collector	2394	60	55	10	2	0	785	229.17	2	24
65	61.00	Minor Arterial	3164	65	55	9	1	0	1415	622.21	2	20
66	56.00	Principal Arterial-Other	28153	55	45	12	0	0	3805	2062.72	6	96
67	63.00	Major Collector	3230	70	55	11	2	0	5760	1266.22	2	26
68	51.15	Minor Arterial	1965	60	55	9	2	0	430	131.31	2	22
69	38.00	Minor Arterial	11707	65	35	10	0	0	450	118.81	2	20
70	43.00	Minor Arterial	5227	70	35	9	2	0	1415	369.15	2	22
71	52.00	Principal Arterial-Other	22851	50	45	12	0	0	1415	1424.24	4	68
72	47.00	Minor Arterial	20300	65	35	11	0	0	1785	405.44	4	44
73	52.00	Principal Arterial-Other	8300	70	55	10	2	0	1480	649.15	2	24
74	50.86	Minor Arterial	2979	60	35	10	3	0	955	469.67	2	26
75	49.25	Minor Arterial	4650	70	45	9	3	0	3730	924.13	2	24
76	59.00	Minor Arterial	3470	65	55	10	4	0	2125	1675.09	2	28

77	51.90	Major Collector	963	60	55	12	2	0	640	551.08	2	28
78	48.00	Principal Arterial-Other	23651	45	35	12	0	0	1135	324.35	4	52
79	45.50	Minor Arterial	6010	70	35	9	0	0	655	438.42	4	54
80	56.00	Minor Arterial	7373	65	35	9	0	0	3280	423.16	2	18
81	33.00	Minor Arterial	4190	40	35	11	0	0	525	227.62	2	22
82	32.00	Minor Arterial	12097	65	35	10	2	0	400	87.28	2	24
83	60.00	Major Collector	2405	60	45	12	8	0	1145	1610.66	2	40
84	35.00	Major Collector	1964	45	35	8	2	0	565	201.72	2	20
85	41.00	Major Collector	8728	60	35	12	2	0	1865	1564.93	2	28
86	54.60	Major Collector	2460	50	45	9	3	0	3230	1705.26	2	24
87	54.00	Major Collector	2827	55	45	10	4	0	1090	317.93	2	28
88	44.00	Major Collector	3208	45	35	10	2	0	475	276.90	2	24
89	42.00	Major Collector	2985	50	45	10	1	0	1600	1396.44	2	22
90	57.50	Major Collector	6407	60	55	12	10	0	1045	1680.58	2	44
91	43.00	Major Collector	721	40	35	10	2	0	1215	1516.60	2	24
92	58.00	Major Collector	2010	50	45	10	3	0	225	273.92	2	26
93	45.55	Minor Arterial	8332	55	45	11	2	0	1185	267.98	2	26
94	58.00	Major Collector	1795	50	45	10	2	0	1180	962.76	2	24
95	58.00	Principal Arterial-Other	7280	60	25	12	3	0	3465	370.65	2	30
96	60.00	Principal Arterial-Other	10924	50	35	11	1	0	2100	1566.53	2	24
97	60.00	Major Collector	2700	60	55	9	3	0	1020	868.58	2	24
98	57.00	Major Collector	2250	60	55	10	2	0	810	804.79	2	24
99	41.75	Major Collector	3930	60	35	9	3	0	2640	672.02	2	24
100	38.00	Minor Arterial	3414	60	35	10	2	0	965	624.91	2	24
101	52.10	Minor Arterial	1965	60	55	9	2	0	610	347.79	2	22
102	51.00	Major Collector	3999	60	55	9	1	0	545	672.83	2	20
103	52.05	Major Collector	4204	70	55	10	4	0	2865	420.31	2	28

104	64.10	Major Collector	3230	70	55	11	2	0	5840	1266.15	2	26
105	60.00	Minor Arterial	3164	65	55	9	1	0	1425	622.15	2	20
106	44.00	Minor Arterial	15020	45	35	11	1	0	370	441.16	2	24
107	37.00	Minor Arterial	9080	55	35	10	0	0	195	144.08	2	20
108	45.00	Major Collector	2394	60	35	10	2	0	630	395.47	2	24
109	61.75	Minor Arterial	3827	60	55	11	2	0	1895	1062.82	2	26
110	49.00	Minor Arterial	7470	65	45	10	3	0	1010	704.05	2	26
111	58.00	Principal Arterial-Other	3911	70	55	10	4	0	2360	1504.70	2	28
112	54.00	Principal Arterial-Other	6429	70	35	10	5	0	2900	1765.61	2	30
113	58.00	Principal Arterial-Other	2537	70	55	10	4	0	2965	1950.39	2	28
114	60.70	Principal Arterial-Other	11134	70	55	12	10	10	4240	1410.83	4	165
115	47.00	Principal Arterial-Other	6332	70	45	12	2	0	1930	1121.24	2	28
116	58.00	Minor Arterial	15000	60	55	12	10	0	3820	3175.98	2	44
117	58.00	Principal Arterial-Other	22386	70	45	11	10	2	2600	658.66	4	64
118	54.00	Minor Arterial	2979	60	45	10	3	0	1035	537.28	2	26
119	51.05	Major Collector	963	60	45	12	2	0	615	357.02	2	28
120	50.35	Minor Arterial	6751	70	45	11	4	0	1560	501.37	2	30
121	44.00	Minor Arterial	20300	65	35	11	0	0	230	137.13	4	44
122	53.00	Minor Arterial	5227	70	55	9	2	0	1405	481.87	2	22
123	53.00	Minor Arterial	2808	70	50	10	3	0	5665	1322.84	2	26
124	51.00	Principal Arterial-Other	22851	50	45	12	0	0	1295	667.05	4	68

APPENDIX C

MODELING APPROACH

The statistic C_p, the adjusted coefficient of determination R^2_{adj}, and the coefficient of determination R^2 would be used to select candidate variables. At the same time, collinearity among the candidate variables based on the regression models should be detected for reducing potential bias. The variance inflation factor (VIF) would be used to test collinearity. The models with high R^2_{adj} (using R^2 in simple linear models) and appropriate C_p then could be chosen.

In the data reduction step, it was difficult to identify extreme data like leverage data through scatter plot. Extreme data would be checked on basis of statistical modes and traffic engineering judgment. Cook's distance (Cook's D), studentized residuals (RSTUDENT), and the hat matrix (Hat Diag H) would be used to detect extreme data. If extreme data exists, then the extreme data would be eliminated and the models should be redeveloped. To fit curves to data, the Box-Cox procedure would be used to identify whether it is necessary to transform variables to exponential or logarithmic curves. The final models would then be obtained following these terms and procedures.

The coefficient of determination R^2 describes how much the independent variables associated with a model can explain the dependant variable. High values of R^2 indicate good regression models. However, R^2 does not account for the number of variables in a multiple regression model. As the number of variables increase, so does R^2. Therefore it is difficult to compare multiple regression models with different numbers of variables by simply using R^2. The adjusted coefficient of determination R^2_{adj} is a better criterion compared to R^2 in a multiple regression model because it also considers the numbers of variables. Higher values of R^2_{adj} usually indicate better fit regression models.

The C_p criterion measures the total mean square error of the fitted values of the regression. The total mean square error includes two components: one from random error, and another from bias. When no bias exists in an estimated regression model, the desired value of C_p is close to the number of coefficients to be estimated. It is recommended that regression models with small C_p value that is close to the number of coefficients are the best models. If the value of C_p is much larger than the number of coefficients, a larger bias is present. Models generated a C_p value larger than 10 usually indicate that important variables are lost. A model with a high R^2_{adj} value and C_p value close to the number of coefficients would well explain the variability of the dependent variable, and therefore could be considered a "reasonable" model.

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