University Transportation Research Center - Region 2

Final Report

Speed and Design Consistency of Combined Horizontal and Vertical Alignments in Two-Lane Rural Roads

Performing Organization: University of Puerto Rico - Mayagüez

April 2014

Sponsor:
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16. Abstract

One of the most important equations in highway design is the formula for the minimum radius of horizontal curve which considers the design speed of the highway, the superelevation, and the side friction factor. Traditionally, differences in the highway vertical alignment features, which are prevalent at areas with rolling and mountainous terrains, are not considered in this part of the design process. Past research has indicated that drivers perceive horizontal curves differently when compared with highway sections in which both horizontal and vertical curves overlap. To address this issue, speed data from over 20,000 vehicles were collected at 41 horizontal curves on ten rural two-lane highway segments in Puerto Rico. Preliminary analyses identified that speed patterns vary across several categories of terrain type, vertical alignment, and horizontal radius. A decision tree algorithm was developed on the basis of the collected data to the database to model the mean speeds along horizontal curves. The results of the model identified the terrain type as the variable that explains the most variability in operational speeds. Changes in vertical alignment (type of vertical curve), lane width, and horizontal radius were also identified as being influential variables, and therefore providing evidence to support the notion that highway design standards should consider the overlapping of horizontal and vertical curves.

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1. BACKGROUND AND LITERATURE REVIEW

Safety is an important aspect (if not the most) of road design, its construction and maintenance. The number of highway fatalities was reduced by 19% in the Unites States (U.S.) between the years 1994 and 2010 [FARS, 2013]; despite of this reduction it is still necessary to improve roadway design in terms of their safety performance functions. The Moving Ahead for Progress in the Century 21st Act (MAP-21) is the newest policy that assigned over $105 billion to transportation programs in order to improve the transportation systems infrastructure. MAP-21 is the first long-term highway agreement enacted since 2005, and it is an attempt to transform current policies, as well as the programmatic framework of investments for conduct the growth and development of the systems; this includes improvements in highway safety [FHWA, 2013].

Highway safety can be assessed in two manners: nominal and substantive safety. **Nominal safety** is analyzed according to a highway system's compliance with the standards, ordinances, guidelines, and other design procedures. Similar to many states, highway design standards in the U.S. territory of Puerto Rico are based on the manuals available from the American Association of State Highway Officials (AASHTO), in particular *A Policy on Geometric Design of Highways and Streets*, commonly referred to as "the Green Book." On the other hand, **substantive safety** is evaluated by the actual crash frequency or the expected number of crashes for a particular highway. The Highway Safety Manual (HSM) was developed to estimate crash frequency, type, and severity by facility. The HSM shows a methodology that considers operational and geometry characteristics in order to forecast the number of crashes by the use of Crash Modification Factors (CMF) and a local Factor (C).

Safety is correlated with design consistency [Polus and Dagan, 1987]. Design consistency is defined as the degree to which highway systems are designed to ensure safety in traffic operation; if design consistency is present, the successive elements of a highway system act in a coordinated way and it results in performance from the drivers, i.e. no crashes [Gibreel et al, 1999]. Operational speed, which is one of the main factors in road geometric design [Sanchez, 2012] is the most common form used to assess the design consistency of a facility because it is quantifiable (it can be measured). The design speed of a highway facility is used to determine its cross section dimensions as well as the horizontal and vertical alignment thus producing a safe system that is consistent with driver's expectations [Figueroa and Tarko, 2004; AASHTO, 2004]. Highway geometric design is considered consistent when the road geometric characteristics correspond to the driver expectancy; therefore there is less work load from the driver and less unsafe maneuvers. Two performance measures that evaluate the design consistency are: the difference between the operational speed and the design speed, and the reduction in operational speed between successive elements [Ottesen and Krammes, 2000]. Substantial differences in operational speed between successive elements can increase erratic maneuvers and crashes [Park et al, 2010; Sanchez, 2012]. AASHTO developed the *Geometric Design on Highways and Streets* in 2004 to promote design consistency and safety in road design; it identifies the design controls and criteria for all types of functional classes and roads. An excellent combination of horizontal and vertical design can improve safety by promoting speed uniformity.

The main objective of road geometric design, from the point of view of physics, is to provide a safe, efficient, and balanced design in all elements of the road; therefore, it is essential to analyze the relationship between speed and curvature [Cardenas, 2002]. AASHTO recommends that the selection of the design speed should take into consideration the topography, the probable operating speed, the adjacent land use, and the highway functional classification [2004]. Highways are a configuration of straight sections (tangents), as well as horizontal and vertical curves, which are influential in operational speeds. Figure 1 shows the free body diagram of a vehicle along a horizontal curve.

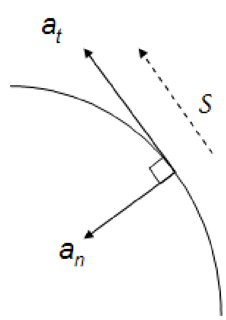


Figure 1. Components of Acceleration in Circular Curves

According to Figure 1, a vehicle traveling at a speed S along a horizontal curve, two acceleration components act upon the vehicle: the normal acceleration a_n and the tangential acceleration a_t. The magnitudes of these accelerations are presented in Equations 1 and 2.

$$a_n = \frac{S^2}{R} \quad (1)$$

$$a_t = \frac{dS}{dT} \quad (2)$$

Where:

- *S* is Speed
- *R* is radii of the horizontal curve
- *dS/dT* is the change of speed in a time interval

The centrifugal force (F) tends to divert the vehicle driving over the curve in a normal trajectory. The magnitude of the centrifugal force is presented in Equation 3.

$$F=ma \tag{3}$$

Where:

- *m* is the mass of the vehicle
- *a* is the radial acceleration with direction to the center of curvature.

Mass and radial acceleration are presented by the follow equations:

$$m = W / g \tag{4}$$

$$a = V^2 / R \tag{5}$$

Where:

- *W* is the weight of the vehicle,
- *g* is the gravity,
- *V* is the speed of the vehicle, and
- *R* is the radii of the horizontal curve.

As shown in Figure 2, there are several components that can be opposed to the centrifugal force: the friction force (F_f), the vehicle weight normal component (W_p), and the superelevation (*e*) applied along the horizontal curve.

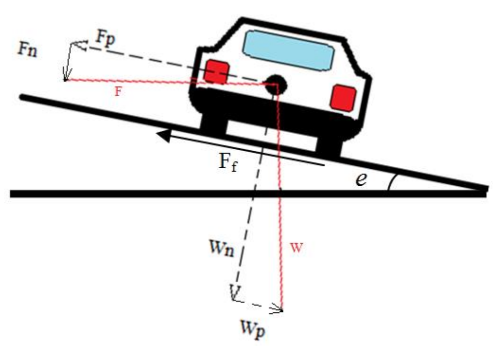


Figure 2. Effect of Superelevation on the Vehicle Driving in a Curve

Also depicted in Figure 2, are the normal and parallel components of all the forces acting on the vehicle. The normal components of the weight of the vehicle, and the centrifugal force (W_n and F_n, respectively) as well as the superelevation, contribute to the vehicle's stability; however their components of these forces parallel to the pavement (W_p and F_p) can do the opposite. From the relationship between the parallel components, four cases are defined:

- Case 1: $W_p = 0$; the centrifugal force achieves its maximum value.
- Case 2: $W_p = F_p$: the resultant force is perpendicular to pavement surface, therefore the centrifugal does not affect the vehicle, and the speed is known as the equilibrium speed.
- Case 3: $W_p < F_p$: the resultant force acts in direction of the centrifugal force, therefore the vehicle tends to slide to the outside of the curve, counterclockwise moment is generated and rollover is typical in light vehicles.
- Case 4: $W_p > F_p$; the resultant force acts in opposite direction to the centrifugal force, therefore the vehicle slides to the inside of the curve; rollover is typical in heavy vehicles.

In all these cases, the tangential acceleration (a_t) is zero, because it is assumed that the vehicle travels at a constant speed along the horizontal curve. Since case 3 is the most popular, the equation of the minimum radius (Equation 6) is the most implemented formula in horizontal curve design [Cardenas, 2002].

$$R_{min} = \frac{V^2}{15(0.01\ e_{max} + f_{max})} \tag{6}$$

Where:

- R_{min} is the minimum horizontal curve radii (feet),
- e_{max} is the maximum superelevation ratio (feet /feet),
- S is the speed (mph), and
- f_{max} is the side friction factor.

Although the minimum radius equation is the most implemented formula in highway design, it does not consider the effect of a slope, or the presence of a vertical curve. When including the slope of a vertical curve in the free body diagram of a vehicle along a horizontal curve, the tangential acceleration (a_t) is no longer zero, as shown in Figure 3.

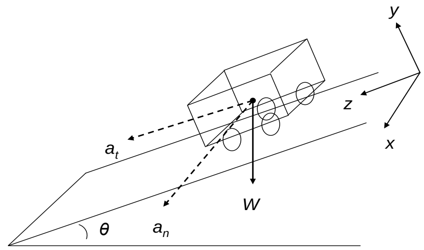


Figure 3. Three-Dimensional Body Diagram of a Vehicle along a Horizontal Curve combined with Downgrade Slope

Since the tangential acceleration (a_t) is no longer assumed to be zero, the equation for minimum radius (Equation 6) is not appropriate for these cases. In addition, the overlapping of horizontal and vertical curves causes driver misperception [Mori et al, 1995]. Hassan and Easa [2003] recognized that horizontal curves, overlapped with crest vertical curves, can produce a horizontal curve that looks sharper to the driver. In the same study the authors identified that when the horizontal curve is overlapped with a sag vertical curve the horizontal curve looks flatter; these perceptions can generate problems in design consistency because they compromise the driver's expectancy.

Besides the fact that the horizontal curve design process does not include the effect of a vertical curve slope, another important shortcoming is that it considers the design speed instead of the operational speed. Fitzpatrick et al. [2007] concluded that drivers travel at operational speeds influenced by the highway geometric features instead of the posted speed, which is based on the design speed.

Based on the literature review performed, the objectives of this research were identified. The main objective of this study was to identify the effect of a vertical curve when combined with a horizontal curve along two-lane rural roads. The specific objectives were:

- Perform a literature review to identify the dependent and independent variables in order to explain the speed behavior along horizontal curves overlapped with vertical curves.
- Identify a selection criterion for the selection of the study sites.
- Collect speed data under free-flow conditions with the purpose to identify acceleration and deceleration patterns related only to the highway features.
- Develop a model to estimate speed behavior along highway segments with varied horizontal and vertical characteristics.

2. RESEARCH METHODOLOGY AND DATA COLLECTION

This section of the report summarizes the most important aspects of the methodology developed in order to perform the research study: the selection of the study sites, data collection on highway features – especially the vertical alignment, and data collection on speeds. Figure 4 shows a flowchart of this process.

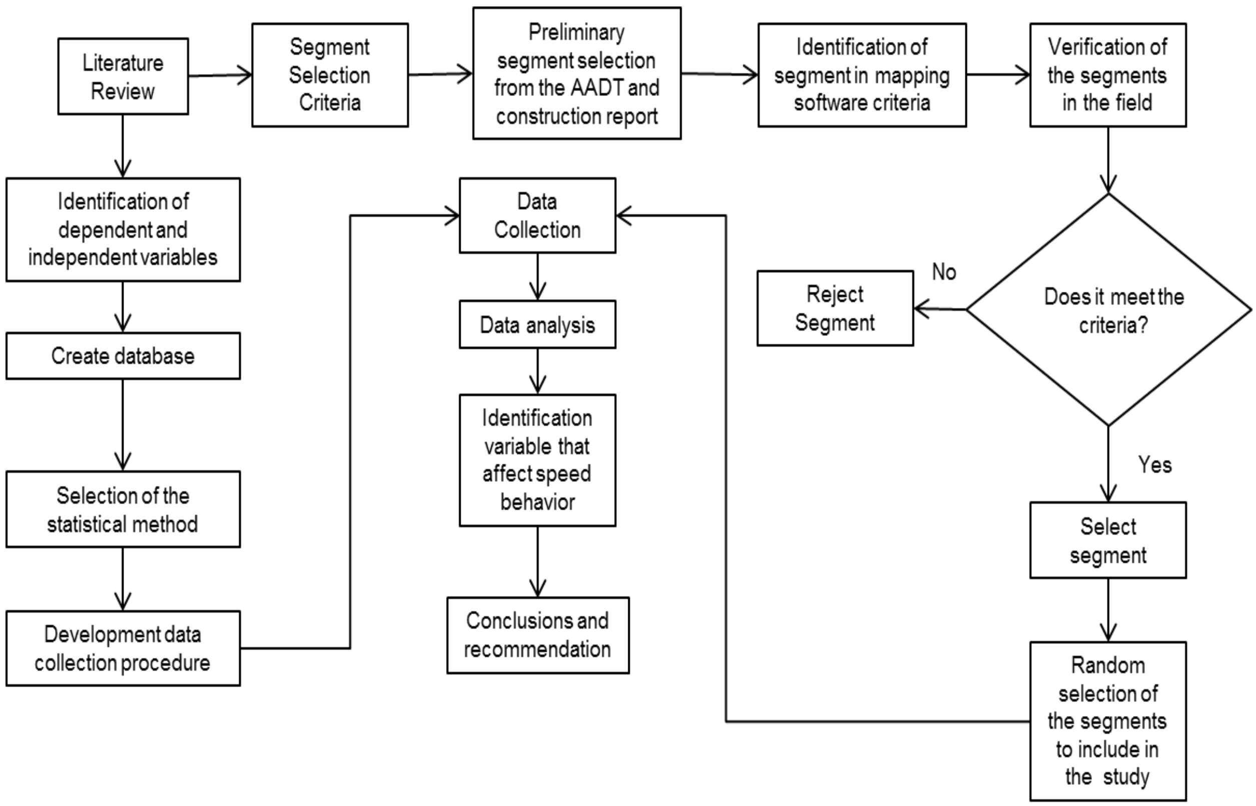
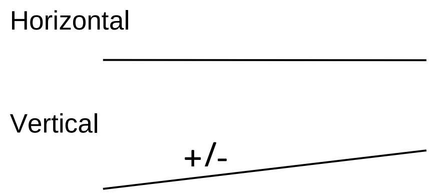


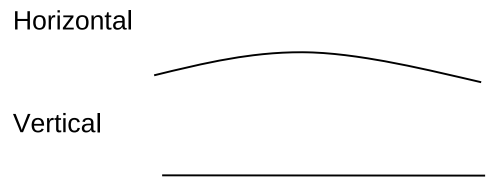
Figure 4. Research Methodology Flowchart

2.1 Identification of Potential Highway Segments

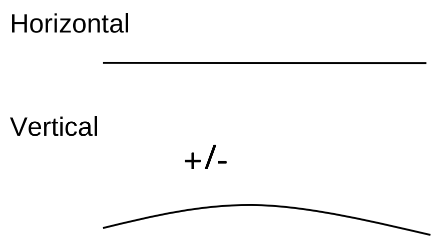
In order to identify the highway sites to be included in the study, a list of desired characteristics was developed. The most important aspect of the database was to include as many geometry configurations as possible, in order to have a representation of every possible scenario. Therefore, several combinations of horizontal and vertical curves, as well as isolated vertical and horizontal curves along two-lane rural roads were highly desired. Four relevant combinations were identified; these are shown in Figure 5..



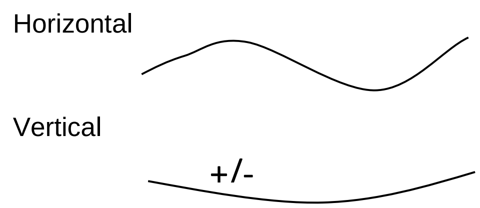
(a) Horizontal tangent, vertical slope



(b) Horizontal curve, vertical tangent



(c) Horizontal tangent, vertical curve



(d) Horizontal curves and vertical curve

Figure 5. Possible Combinations of Horizontal and Vertical Alignments

Figure 5(a) shows the case in which there is no change in horizontal alignment, but there is the presence of a constant slope. Figure 5(b) represents the case when there is a horizontal curve in flat terrain. The presence of an isolated vertical curve (crest or sag) along a horizontal tangent is presented in Figure 5(c), while the scenario of the overlapping of horizontal and vertical curves is shown in Figure 5(d).

In addition, a selection criterion was developed in order to identify potential study sites. Preliminary three characteristics were selected: annual average daily Traffic (AADT), mapping services, and pavement conditions. The first step was to obtain AADT values from the Department of Transportation and Public Works (DTPW) of Puerto Rico; highways with AADT between 1,000 vehicles per day (vpd) and 10,000 vpd were identified as potential study sites. This range of values was selected in order to increase the probability of collecting data from free-flow vehicles (please read Section 2.3 for more information about free-flow vehicles).

The second step was to locate the potential candidate segments using mapping services available on the Internet. These were very useful in identifying rural areas and highway segments with a wide variety of horizontal curve radii. The third and last step was to perform field visits in order to corroborate whether the potential sites were indeed appropriate for the research study; this included highway segments in good pavement conditions and free of signalized intersections. Table 1 shows the selection criteria developed to identify appropriate highway segments to be included in the study.

Table 1. General Selection Criteria of Candidate Segments

Selection Characteristic	Criteria
AADT	1,000 -10,000 vpd
Zone description	Rural
Posted Speed limit	35 mph or higher
Terrain	All types
Pavement condition	Surface in good condition
Pavement surface type	Rigid to Flexible
Access control	No signalized intersections
Segment Length	Over 0.5 miles
Cross section	Two-lane, two way
Slope	No restriction

After this process, a total of 18 segments in the western area of Puerto Rico were selected as candidate sites in accordance to the selection criterion developed. Because of time and financial restrictions, a total of 10 highway segments were included in the study. Information on the selected study sites is presented in *Section 3.1*.

2.2 Data Collection on Highway Geometric Features

The data collection of highway characteristics was started on May, 2013. The characteristics included in the database can be categorized as cross section features, segments' characteristics, horizontal alignment, and vertical alignment.

Cross section characteristics included shoulder width (unpaved, and unpaved), lane width, travel way width, pavement width, clear zone, vertical slope, sight distance, and presence of obstruction and type, if any. Figure 6 shows the cross section features at one of the study sites.

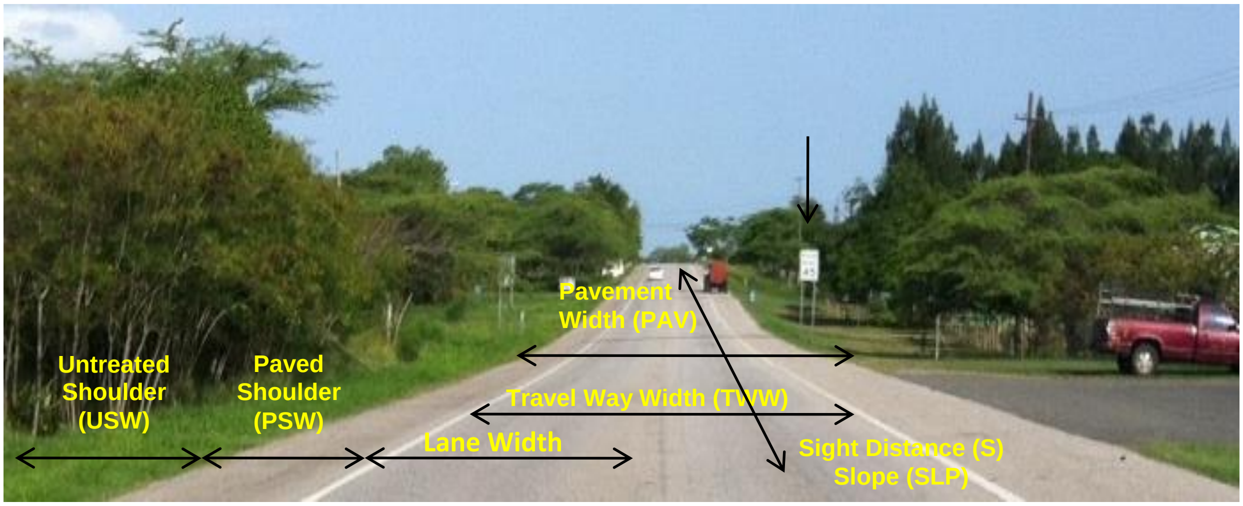


Figure 6. Cross Sectional Characteristics

In addition to the cross section elements, information on the posted speed limit of the highway segments, as well as the number of accesses along the segment, and the terrain type (level, rolling, or mountainous) was collected. The type of terrain was determined according to the Highway Design Manual of Puerto Rico in which the terrain conditions are defined as follows [DTPW, 1979]:

- Level – generally flat terrain where sight distances, as governed by both horizontal and vertical restrictions, are generally long or could be made to be so without construction difficulty or major expense.
- Rolling – terrain where the natural slopes consistently rise above and fall below the highway grade line and where occasional steep slopes offer some restriction to normal highway horizontal and vertical alignment.
- Mountainous – Terrain where longitudinal and transverse changes in elevation of the ground with respect to the highway are abrupt and where the roadbed is obtained by frequent benching or side hill excavation.

For the presence of each horizontal curve, the following information was collected: middle ordinate, chord, superelevation rate, and the length of the horizontal curve. The value of the radius of each was then calculated with the values of the middle ordinate and the chord.

Desired information on vertical alignment included the following elements: approach and departure slopes, length of vertical curve, and the rate of divergence of the slopes (the algebraic difference in slopes). Since no information on vertical alignment was readily available, this information was measured in the field. To collect vertical data two techniques were used: handheld GPS and ArcGis data.

After initially collecting vertical data along some highway segments using a handheld GPS, it was observed that the equipment was sometimes collecting erroneous data. According to the manufacturer, the equipment has an accuracy of ±10 ft; however the output showed sometimes a difference in elevation of 40 ft between two points that that were 30 feet apart. An example of two of these situations could be observed from the vertical data collected along highway PR-108 which is shown in Figure 7.

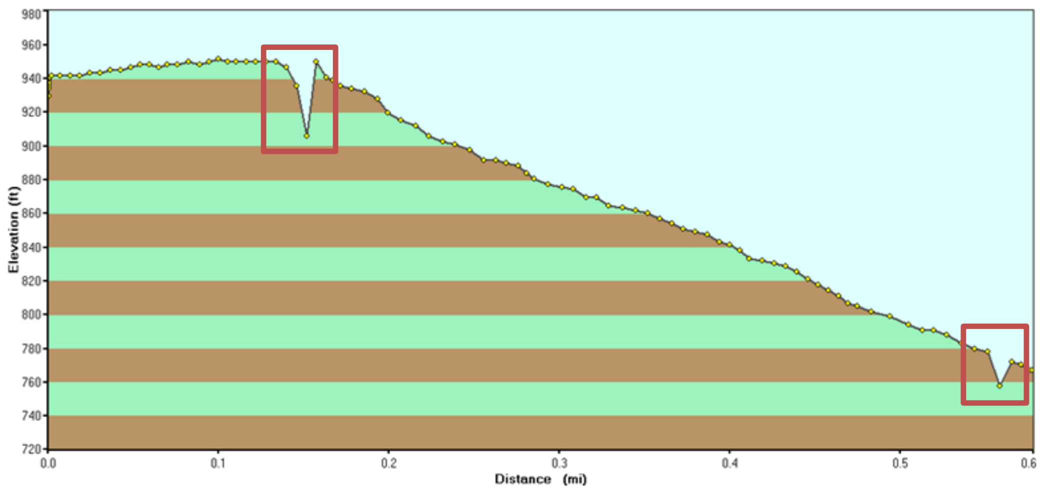


Figure 7. Vertical Data along PR-108 Using a Handheld GPS

The lack of accuracy caused by the handheld GPS could have been due an insufficient number of satellites in the zone, since this equipment uses between 2 to 5 satellites to collect data. Another reason for this lack of accuracy could have been due to the excessive vegetation along the roads; an example of this is shown in Figure 8 where high trees with extensive foliage were observed along the highway PR-108.

Figure 8. Extensive Foliage along PR-108

In order to compensate for the lack of accuracy given by the handheld GPS, the research team decided to use ArcGis software to collect vertical information along the highway segments, which has an accuracy of ±3 ft. Figure 9 shows the output provided by this software along PR-108.

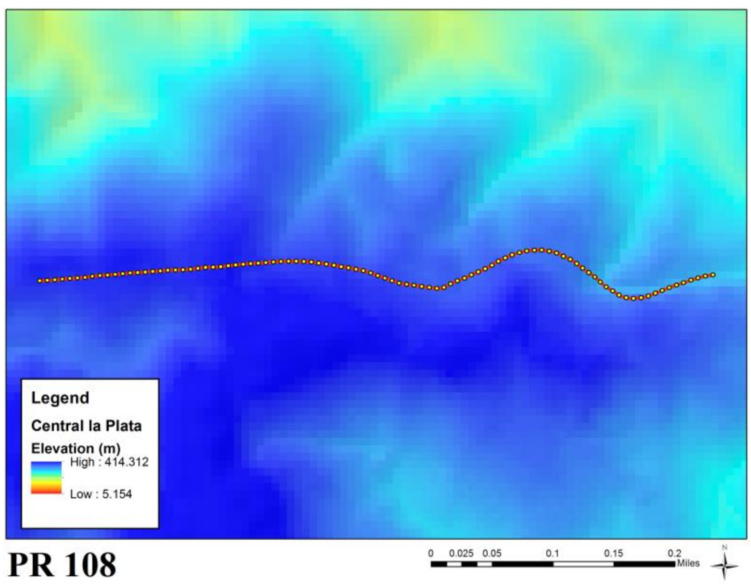


Figure 9. ArcGis Output for PR-108

2.3 Data Collection on Speed Data

In order to obtain information from vehicles that are solely influenced by the highway geometric characteristics, speed data was collected only from free-flow vehicles. A free-flow vehicle is identified as a vehicle that has a minimum time headway of 5 seconds, thus its speed is not influenced by the speed of a leading vehicle [McFadden and Elefteriadou, 2000]. In addition, speed data was only collected from passenger vehicles during daylight and dry pavement conditions.

Since it was desired to obtain information of the speed patterns along the highway segments, especially along the horizontal curves, the data equipment was placed at 5 locations in order to "track vehicles". The five locations were: in the approach tangent (T1), at the beginning of the curve (PC), in the middle of the curve, at the end of the curve (PT), and in the departure tangent (T2). Only data from free-flow vehicles that were collected at all five locations was considered in the data analyses.

A minimum of 108 free-flow vehicles was desired for each study site. This sample size was determined by the following equation [Institute of Transportation Engineers (ed. Robertson), 1994]:

$$N = \left(S * \frac{K}{E}\right)^2 \tag{7}$$

Where:

- *N* = minimum number of measured speeds,
- *S* = standard deviation (mph),
- *K* = constant corresponding to the desired confidence level, and
- *E* = permitted error or tolerance in the average speed estimated (mph).

Box and Oppenlander [1976] recommended that for two-lane rural roads a representative value of the standard deviation (*S*) was 5.3 mph. The value of the constant *K* for a 95% confidence level is 1.96. Using a permitted error (*E*) of ±1 mph, and substituting all these values in Equation (7) gives a sample size of 108 observations.

3. DESCRIPTIVE STATISTICS

This section of the report summarizes the information obtained from the data collection process, including the general description of the study sites and the geometric features of the highway segments included in the study.

3.1 Study Sites

As mentioned previously, 18 highway segments in rural areas of Puerto Rico were initially selected according to the selection criteria developed (*see Section 2.1*); due to time and budget restrictions data was collected from 10 of these segments. Figure 10 shows the location of these study sites and Table 2 summarizes the characteristics of the highway segments.

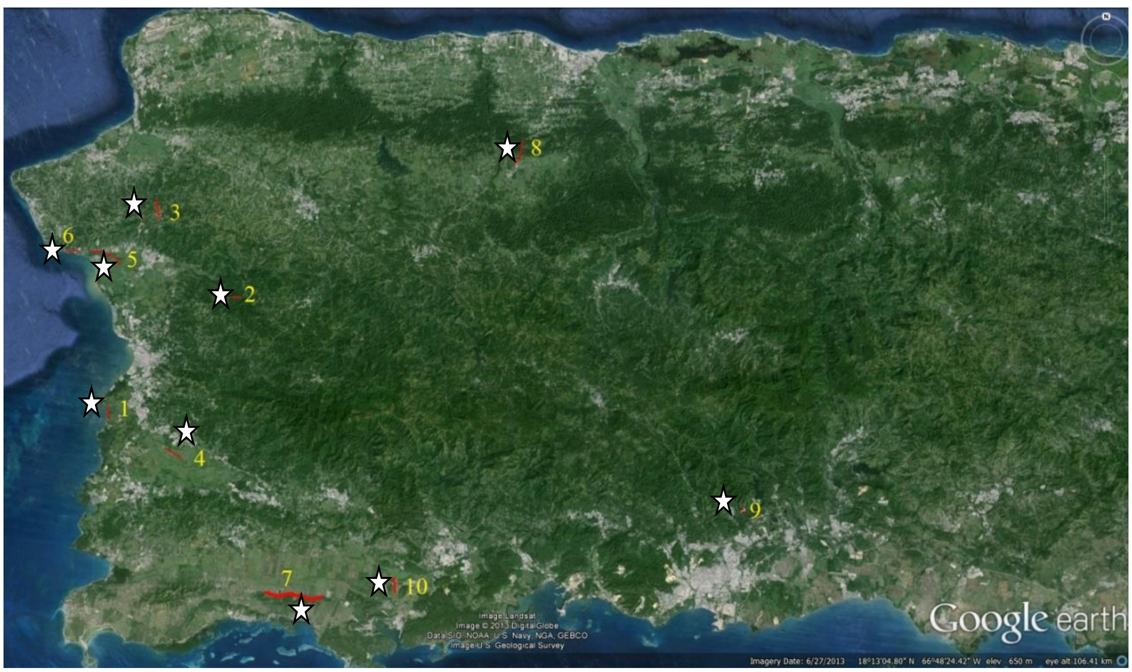


Figure 10. Location of the Selected Segments (Source: Google Earth)

Table 2. General Characteristics of the Selected Segments

Site ID	Highway	Posted Speed Limit (mph)	Length of Segment (mi)	Type of Terrain	Municipality
1	PR-102	35	0.75	Level	Cabo Rojo
2	PR-108	35	0.57	Mountainous	Añasco
3	PR-110	35	1.38	Mountainous	Anasco-Moca
4	PR-114	35	1.35	Level	Hormigueros
5	PR-115a	35	2.15	Level	Añasco
6	PR-115b	35	0.81	Rolling	Añasco
7	PR-116	45	2.87	Rolling	Lajas
8	PR-129	45	1.67	Rolling	Hatillo
9	PR-139	35	0.58	Mountainous	Ponce
10	PR-332	35	0.90	Level	Guánica

As shown in Table 2, ten highway segments were identified along 9 roads in 8 municipalities of Puerto Rico. The posted speed limit was mostly 35 mph except in two study sites (Sites ID 7 and 8) where the posted speed limit was 45 mph. The study sites included representation from the three types of terrain (level, rolling, and mountainous) and the length of the highway segments ranged from 0.5 to approximately three miles.

3.2 Highway Features

Data collection of the highway characteristics included obtaining information on the number of horizontal curves at each highway segment. In addition, the research team identified the number of isolated vertical curves (no presence of horizontal curves), as well as the presence of isolated tangents. A total of 41 horizontal curves, five isolated vertical curves, and five isolated tangents were present along the highway segments selected for the study, as shown in Table 3.

Table 3. Characteristics of the Selected Segments

Segment Code	Segment	No. of Horizontal Curves	No. of Isolated Vertical Curves	No. of Isolated Tangents
1	PR-102	6	-	-
2	PR-108	4	-	-
3	PR-110	9	-	-
4	PR-114	1	-	2
5	PR-115a	2	-	2
6	PR-115b	5	1	-
7	PR-116	5	3	-
8	PR-129	2	1	-
9	PR-139	5	-	-
10	PR-332	2	-	1
Total		***41***	***5***	***5***

As indicated in Section 2.2, data was collected on the values for the cross sectional characteristics of the highway, as well as values of both horizontal (radius and length) and vertical (slope) alignment. Since speed data was collected at several places along the horizontal curves, information on the highway features were also collected at each of these locations. Speed data, as well as highway characteristics, were then collected at a total of 190 spot locations. In addition, the database included information from 24,250 free-flow passenger vehicles. Table 4 summarizes the descriptive statistics for the highway features, as well as vehicle speeds.

Table 4. Descriptive Statistics for Geometric Features of the Highway Segments

Highway Characteristic	**Mean**	**Std. Deviation**	**Minimum**	**Maximum**
Sight Distance (ft)	534.52	357.16	105	1767
Grade (%)	0.97	4.68	-10	10.7
Lane Width (ft)	10.6	1.6	6.7	12.6
Travel Way Width (ft)	21.1	3.2	13.3	25.2
Pavement Width (ft)	29.2	10.8	15.1	54.6
Paved Shoulder Width (ft)	4.1	4.3	0	18.9
Clear Zone Distance (ft)	11	7.2	1.3	52.5
Curve Radius (ft)	847.05	833.68	90	4090
Max. Superelevation (%)	5.20	1.58	2	8
Curve Length (m)	79.77	57.20	19.7	250
Mean Free Flow Speed (mph)	37.99	8.00	16.4	78.04
85th Percentile Free Flow Speed (mph)	43.13	7.72	26.67	61.47

As presented in Table 4, the dimensions of the cross section elements show a large variability, which was one of the objectives of the study. The average of the observed free flow speeds was 37.99 MPH with a range of 61.64 MPH; however the posted speeds in selected horizontal curves were between 35 and 45 mph. The 85^{th} percentile of the free flow speeds was 43.13 MPH with a range of 34.81 mph (55.69 Km/h). This large variability in speeds could be an indication that the geometric features of the highways are influential on drivers' selection of operating speeds, as suggested by Figueroa and Tarko [2004].

4. DATA ANALYSES

In order to study the influence of changes in vertical alignment on operational speeds along horizontal curves, the first step in the data analyses process was to identify speed patterns by several classification categories. A decision tree algorithm was selected for modeling the changes in these speeds due to changes in highway geometric features.

4.1 Preliminary Speed Analyses

In order to gain insight on speed behavior, preliminary analyses were performed by aggregating the data according to three characteristics: terrain type, pavement markings, and range of radius.

The first analysis was to observe speed patterns according to terrain type. Of the 190 spot locations where speed data was collected, 55 were collected in level terrain, 55 in rolling terrain, and the remaining 80 in mountainous terrain; the sample size (number of vehicles) at each of these categories was 5,920, 5,993, and 12,337, respectively. Figure 11 shows the speed patterns for each terrain type along horizontal curves, and Table 5 presents the descriptive statistics.

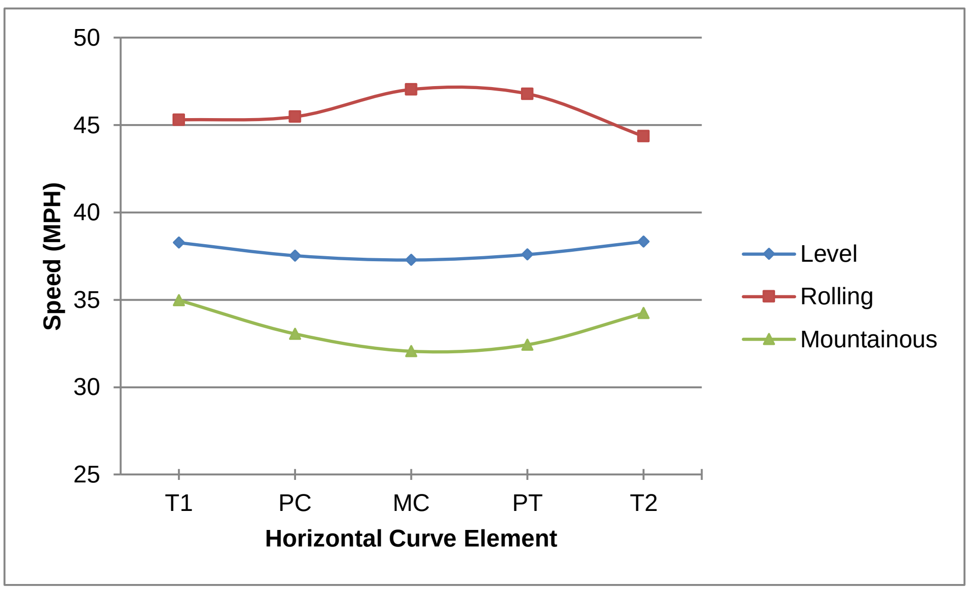


Figure 11. Mean Speed in Horizontal Curves Aggregated by Terrain (T1- Approach Tangent, PC- Beginning of Curve, MC- Middle of Curve, PT- End of Curve, T2- Departure Tangent)

Table 5. Mean Speed and Standard Deviation for Speed Data by Terrain Type

Horizontal Curve Element	Level (N=5,920)		Rolling (N=5,993)		Mountainous (N=12,337)	
	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev

T1	38.28	6.10	45.30	7.31	34.98	5.94
PC	37.53	6.02	45.48	6.63	33.06	5.88
MC	37.28	6.40	47.04	6.79	32.06	5.82
PT	37.59	6.74	46.79	6.69	32.44	5.90
T2	38.34	6.23	44.37	6.68	34.24	5.41
Mean and standard deviation are in mph						

The preliminary analyses by terrain type indicate that speeds along horizontal curves in rolling terrain are higher than those in level and mountainous terrains; lowest speeds were encountered in mountainous terrains. In addition, speeds along horizontal curves in both level and mountainous terrains are in accordance with the theory; past researchers have indicated that the slowest speeds occur in the middle of the horizontal curve [Misaghi, 2003; Fitzpatrick and Collins, 2000]. In rolling terrain, the drivers' speeds appear to reach their maximum towards the end of the horizontal curve, which is not consistent with the theory; this could have been due to the functional classification of the road segment at each level. The standard deviations of speeds are also higher in rolling terrains, indicating that there is more variability in speeds at these locations.

Speed data was also aggregated according to the radius of horizontal curve. A research conducted by McFadden [1998] identified four categories according to the range of horizontal curve radius; the research team decided to aggregate the speed data according to these categories. The sample sizes for categories 1, 2, 3, and 4 were 17,140, 4,071, 2,642, and 397, respectively. The range of horizontal curve radii for each category, as well as the mean speed, and speed standard deviation at the five locations are shown in Table 6; a graphical presentation is depicted in Figure 12.

Table 6. Mean Speed and Standard Deviation for the Data Aggregated by Radii

Horizontal Curve Element	Category 1 (N=17,140) Radius Range 570-820 ft		Category 2 (N=4,071) Radius Range 820-1425 ft		Category 3 (N = 2,642) Radius Range 1425-2860 ft		Category 4 (N = 397) Radius Range > 2860 ft	
	Mean	St Dev	Mean	St Dev	Mean	St Dev	Mean	St Dev
T1	36.23	6.32	41.01	6.89	48.96	7.23	36.41	5.51
PC	34.49	6.25	41.57	7.02	48.53	6.39	38.34	5.78
MC	33.80	6.64	42.13	7.28	49.96	6.52	37.53	5.53
PT	33.99	6.86	42.13	6.73	49.71	6.55	35.54	5.06
T2	35.54	6.04	41.13	6.90	46.98	6.43	37.10	5.90
Mean and standard deviation are in mph								

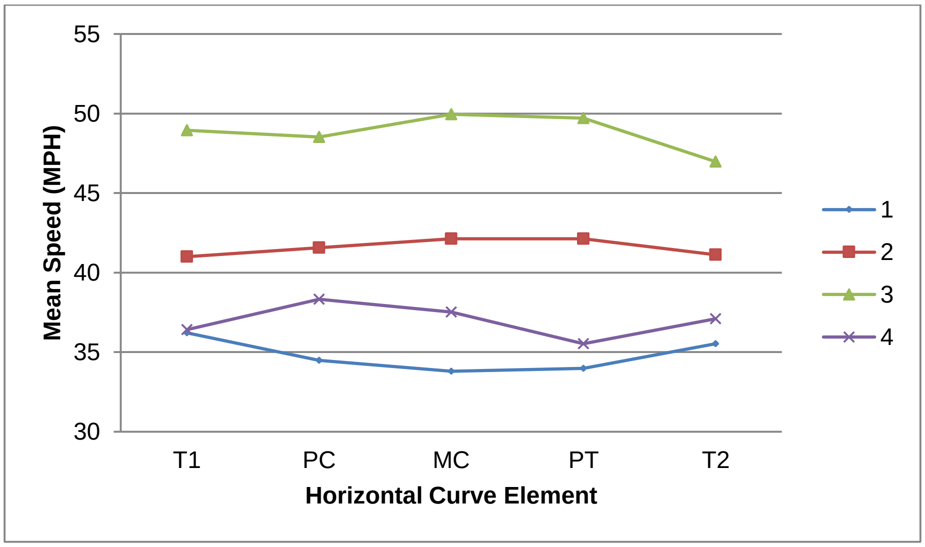


Figure 12. Mean Speed along Horizontal Curves by Radii Category

When aggregating speed data according to range of horizontal curve radii, it can be observed that speeds tend to increase (as well as their standard deviations), as the horizontal radius increases, except when the radius is over 2860 ft (Category 4); this could have been due to the small sample size for this category. From Figure 12, it can also be observed that the only category in which speeds are in accordance with the theory (drivers slow their speeds entering the curve and increase their speeds toward the end of the curve) is for horizontal curves with a radius less than 820 ft (Category 1).

Finally, data were aggregated according to the vertical alignment in each horizontal curve. Seven categories were identified: level, negative and positive constant slope (downgrade and upgrade, respectively), crest vertical curve, sag vertical curve, and the transition from crest to a sag vertical curve and vice versa. Figure 13 shows the speed profiles along horizontal curves for each category.

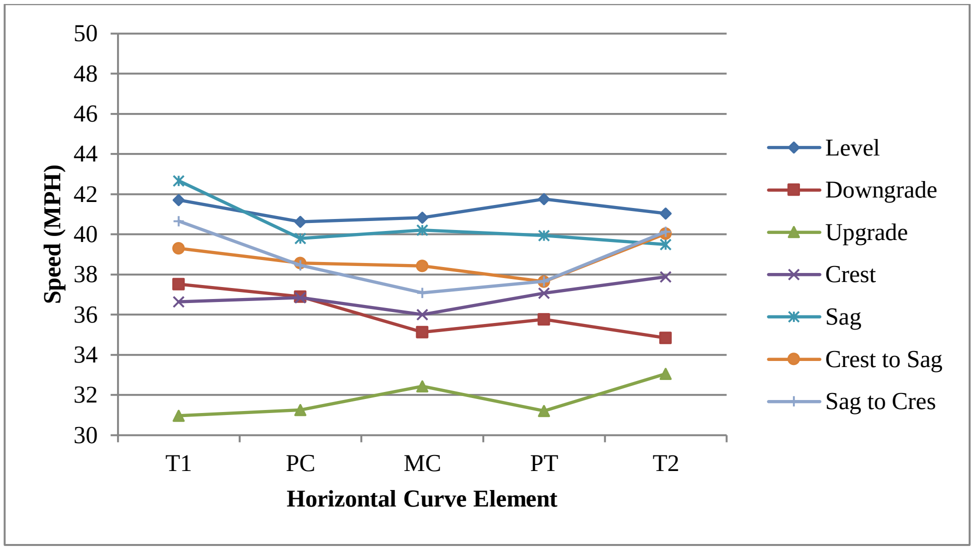


Figure 13. Mean Speed along Horizontal Curves by Vertical Alignment Category

As seen in Figure 13, mean speeds along horizontal curves that have no changes in vertical alignment (level category) are between the 40 and 42 mph. Along curves that have a constant upgrade, means speeds are lower than in any other type of vertical alignment; speeds increase until the middle of the curve, then decrease afterwards and reach a maximum in the departure tangent (T2 – after the horizontal curve). For constant downgrades, speeds decrease until the middle of the horizontal curve, then fluctuate afterwards.

When there is a crest vertical curve, the lowest speeds occur in the middle of the horizontal curve. Speeds in sag vertical curves are higher than in crest vertical curves, and the pattern is similar to speeds in downgrades. Finally when a combination of vertical curves – either sag-to-crest or crest-to-sag – is present along horizontal curves, speeds decrease until a point in the horizontal curve and then increase towards the departure tangent.

4.2 Decision Tree Model

Speed data was modeled applying a decision tree classification model; this model is very useful when the independent variables can be divided into classes [IBM, 2012]. In addition, decision trees can incorporate many types of independent variables (nominal, ordinal, or continuous) in the same model, even if the dependent variable is continuous.

Decision tree models, with the application of algorithms, are able to identify patterns in the database by splitting the predictors (independent variables) into classes. Some of the advantages of applying decision tree models are [Roberts, 1999; Hallmark et al., 2001]:

1. The data does not have to follow a particular distribution as opposed to traditional regression analysis, since decision trees are nonparametric methods.
2. Decision trees are resistant to the effects of outliers.
3. This model chooses only the most important independent variables as well as the values of those variables that result in the maximum reduction in variability of the dependent variable.
4. The results obtained are constant, regardless of the transformation of the independent variables.

Many algorithms are available to develop a tree decision model. The simplest one is the Classification and Regression (C&R) tree which starts by identifying the split that will result in the best prediction; this process is recursively and the algorithm continues splitting the data until the tree is finished [IBM, 2012]. The C&R algorithm always splits the data into two subgroups and it was the algorithm selected for the model development.

The variables of lane width, roadway width (paved roadway width plus lateral clear zones), and radius of horizontal curve were divided into classes for model development purposes. Lane width was divided into 4 classes according to the levels presented in the Highway Capacity Manual: less than 10 ft, between 10 and 11 ft, between 11 and 12 ft, and over 12 ft. The width of the paved roadway was divided into three classes: less than 30ft, between 30 and 50 ft, and over 50 ft. Finally the radius of horizontal curves was divided into the three classes similar to the ones presented in Section 4.1: less than 820 ft, between 820 ft and 1,425ft, and over 1,425 ft. The frequency and the percent for each of the classes for these three variables are shown in Tables 7, 8, and 9.

Table 7. Lane Width Labels Frequency

Lane Width Label	Range	Frequency	Percent	Cumulative Percent
1	< 10 ft	3698	15.2	15.2
2	≥ 10 and < 11	10460	43.1	58.4
3	≥ 11 and < 12	4561	18.8	77.2
4	≥ 12 ft	5531	22.8	100.0

Table 8. Radii Labels Frequency

Road Width Label	Range	Frequency	Percent	Cumulative Percent
1	< 820 ft	17140	70.7	70.7
2	≥ 820 and < 1,425	3565	14.7	85.4
3	≥ 1,425	3545	14.6	100.0

Table 9. Road Width Labels Frequency

Radii Label	Range	Frequency	Percent	Cumulative Percent
1	< 30 ft	7854	32.4	32.4
2	≥ 30 and < 50ft	3076	12.7	45.1
3	≥ 50 and < 70ft	3998	16.5	61.6
4	≥ 70 ft	9322	38.4	100.0

Once the database was finished, the decision tree algorithm was developed using the Statistical Package for Social Sciences (SPSS) software. The decision tree model based on the variables found to explain the variability on speeds is shown in Figure 14; Table 10 summarizes the information provided by the model (please see Appendix A for the complete output of the model).

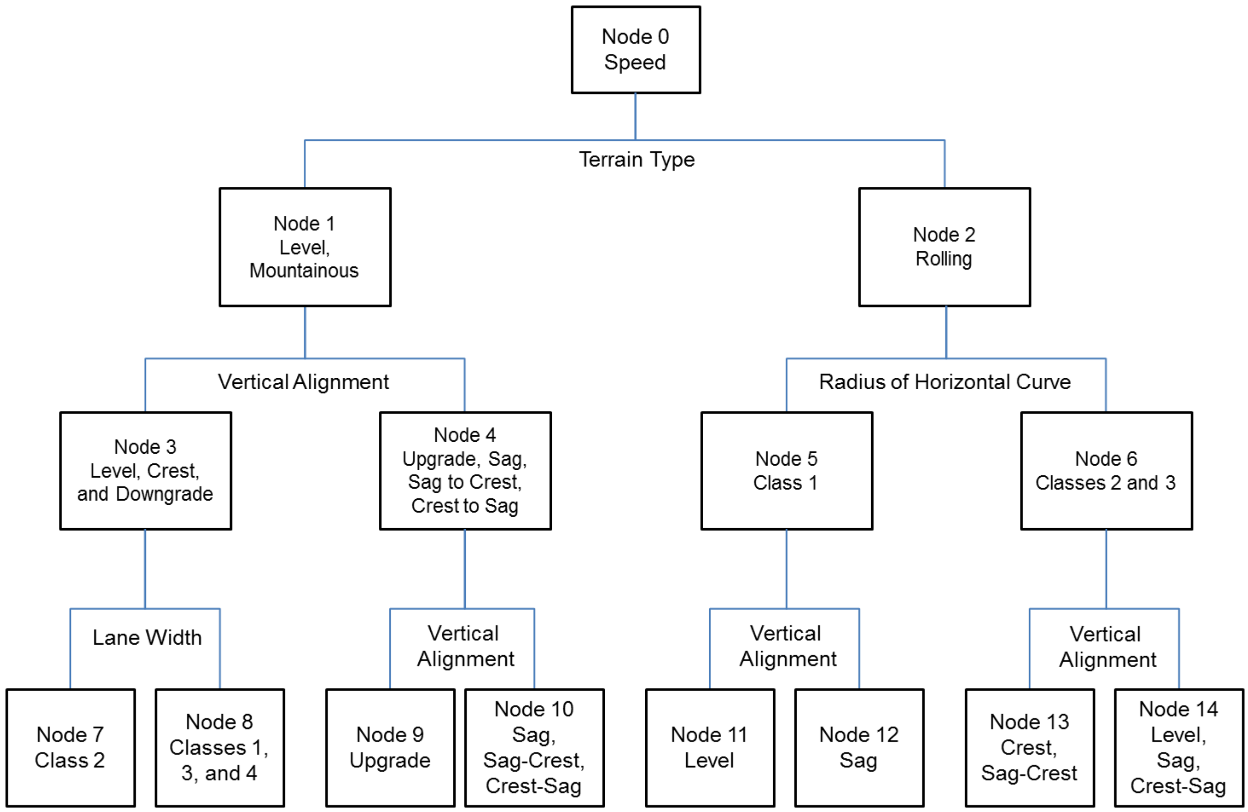


Figure 14. Decision Tree Model for Predicting Speeds

Table 10. Description of Nodes of the Decision Tree Model

Node	Mean (mph)	Std. Dev (mph)	N	Percent of data	Primary Independent Variable		
					Variable	Improvement	Split Values
0	37.82	8.29	24250	100.0%	n/a	n/a	n/a
1	34.70	6.05	18257	75.3%	Terrain	29.74%	Level; Mountainous
2	47.34	6.79	5993	24.7%			Rolling
3	36.41	5.72	12252	50.5%	Vertical Alignment	4.52%	Level; Crest; downgrade
4	31.20	5.13	6005	24.8%			Upgrade; Sag; Sag to Crest; Crest to Sag
5	42.91	5.45	1058	4.4%	Radius	1.04%	Class 1
6	48.29	6.68	4935	20.4%			Class 2 and 3
7	31.48	4.79	1559	6.4%	Lane Width	1.79%	Class 2
8	37.13	5.48	10693	44.1%			Classes 1, 3, and 4
9	32.98	4.93	2507	10.3%	Vertical Alignment	0.56%	Upgrade
10	29.92	4.89	3498	14.4%			Sag; Sag to Crest; Crest to Sag
11	38.98	4.90	460	1.9%	Vertical Alignment	0.52%	Level
12	45.93	3.62	598	2.5%			Sag
13	44.88	5.96	1831	7.6%	Vertical Alignment	1.40%	Crest; Sag to Crest
14	50.30	6.25	3104	12.8%			Level; Sag; Crest to Sag

According to the model developed, the four variables that were identified as explaining the greatest amount of variability on operational speeds along horizontal curves were terrain type, vertical alignment, radius of horizontal curve, and lane width. The decision tree produced is read as follow: the mean speed of 100% of the database (Node 0) is 37.8 mph. The first split is based on type of terrain; mean speed in level and mountainous terrains (Node 1) is 34.7 mph while in rolling terrains (Node 2) is 47.3 mph. Then the model indicates that in level and mountainous terrains the next influential variable on speeds is the vertical alignment (Nodes 3 and 4) while on rolling terrain the radius of horizontal curves (Nodes 5 and 6) explains the greatest variability on operational speeds. The vertical alignment is then identified again as influential variable as it is present in 6 more nodes (Nodes 9 through 14) while lane width is found to be influential on speeds along horizontal curves in level terrains and mountainous terrains that have crest vertical curves and constant downgrade slopes.

Besides indicating the mean speed value and the standard deviation at each node, additional information is provided by the model, such as the number of observations included in each split and the improvement of the model at each split (shown in Table 10). The improvement is defined as “the change in impurity if split using the surrogate” and is a measure of relative importance [SPSS, 1998]. For example the model reports that the improvement of the first split (Node 0 is split in Nodes 1 and 2) is 29.74; this means that the impurity of the first split is 29.74% less than the impurity of the root node (Node 0).

5. CONCLUSIONS AND RECOMMENDATIONS

The most common formula used in highway design – the equation for minimum radius of horizontal curve – does not take into account the features of the vertical alignment. Past research studies have identified that the combination of horizontal and vertical curves are influential on driver behavior. A safe highway system should be designed considering driver's expectancy of the road.

Speed data was collected along 10 highway segment in two-lane rural roads in Puerto Rico where there were present several combinations in vertical alignment and horizontal curves. The geometric characteristics of the highway were also included in the database.

For this study, speeds were initially aggregated by terrain type as well as radius of horizontal curve to gain insight on speed patterns. It was determined that level and mountainous terrains show lower speeds along horizontal curves when compared to rolling terrains. In addition, speeds along horizontal curves in rolling terrains have different patterns than those in the other two categories, thus providing evidence that vertical changes are influential on driving behavior as represented by these changes in operational speeds. When considering the radius of the horizontal curve, variation in speeds patterns was also observed; in some cases the lowest speeds did not take place in the middle of the curve, a general conclusion from previous studies.

Speed data were also aggregated according to the vertical alignment along the horizontal curve. The following seven categories were used to aggregate the data: level, downgrade, upgrade, crest, sag, crest-to-sag, and sag-to-crest. Speed profiles also showed different patterns according to the category. It was observed, for example, that for horizontal curves in the upgrade direction, speeds increase until the middle of the curve, then decelerate and accelerate again after this point.

A decision tree algorithm was used for deeper speed analyses; the model developed further proves that vertical alignment is influential on driving behavior since the variable terrain type was selected for the first split. The other variables that were identified as influential on operational speeds along horizontal curves were vertical alignment, radius of horizontal curve, and lane width.

The results of this study indicate that speed patterns along horizontal curves vary greatly according to changes in vertical alignment; therefore it is necessary to perform additional research in this area. It is recommended that future studies focus on the seven vertical alignment categories that were included in this study and that can be encountered along two-lane rural roads since speed patterns along horizontal curves differ across these categories. The conclusions of these studies could be used for developing highway design standards that promote safe driving behavior.

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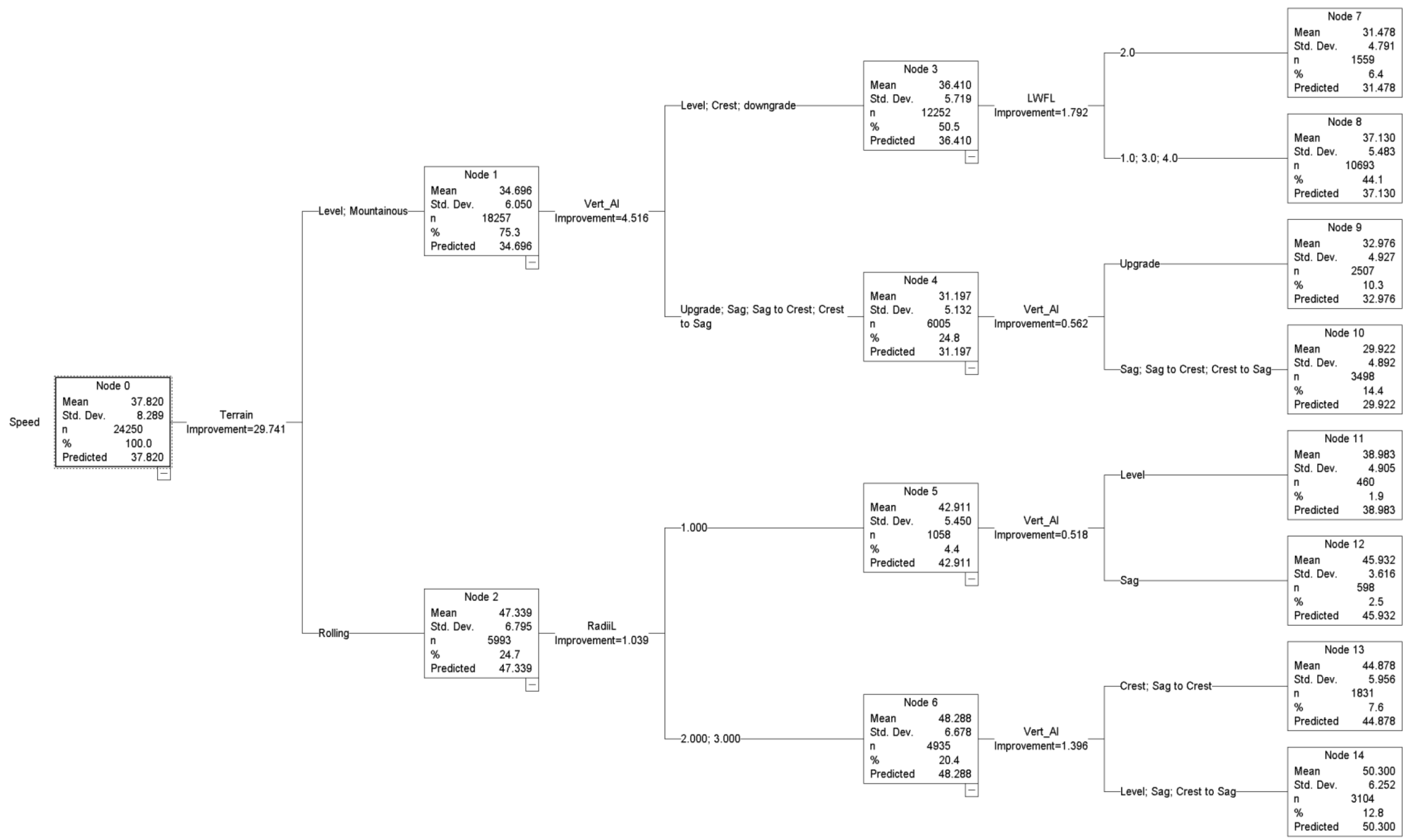
Statistical Package for Social Sciences: *AnswerTree™ 2.0 User's Guide*; Copyright © 1998 by SPSS Inc.

APPENDIX

Decision Tree Model Output, SPSS


Speed
Node 0
Mean 37.820
Std. Dev. 8.289
n 24250
% 100.0
Predicted 37.820
Terrain
Improvement=29.741
Level; Mountainous
Node 1
Mean 34.696
Std. Dev. 6.050
n 18257
% 75.3
Predicted 34.696
Vert_Al
Improvement=4.516
Level; Crest; downgrade
Node 3
Mean 36.410
Std. Dev. 5.719
n 12252
% 50.5
Predicted 36.410
LWFL
Improvement=1.792
2.0
Node 7
Mean 31.478
Std. Dev. 4.791
n 1559
% 6.4
Predicted 31.478
1.0; 3.0; 4.0
Node 8
Mean 37.130
Std. Dev. 5.483
n 10693
% 44.1
Predicted 37.130
Upgrade; Sag; Sag to Crest; Crest to Sag
Node 4
Mean 31.197
Std. Dev. 5.132
n 6005
% 24.8
Predicted 31.197
Vert_Al
Improvement=0.562
Upgrade
Node 9
Mean 32.976
Std. Dev. 4.927
n 2507
% 10.3
Predicted 32.976
Sag; Sag to Crest; Crest to Sag
Node 10
Mean 29.922
Std. Dev. 4.892
n 3498
% 14.4
Predicted 29.922
Rolling
Node 2
Mean 47.339
Std. Dev. 6.795
n 5993
% 24.7
Predicted 47.339
RadiiL
Improvement=1.039
1.000
Node 5
Mean 42.911
Std. Dev. 5.450
n 1058
% 4.4
Predicted 42.911
Vert_Al
Improvement=0.518
Level
Node 11
Mean 38.983
Std. Dev. 4.905
n 460
% 1.9
Predicted 38.983
Sag
Node 12
Mean 45.932
Std. Dev. 3.616
n 598
% 2.5
Predicted 45.932
2.000; 3.000
Node 6
Mean 48.288
Std. Dev. 6.678
n 4935
% 20.4
Predicted 48.288
Vert_Al
Improvement=1.396
Crest; Sag to Crest
Node 13
Mean 44.878
Std. Dev. 5.956
n 1831
% 7.6
Predicted 44.878
Level; Sag; Crest to Sag
Node 14
Mean 50.300
Std. Dev. 6.252
n 3104
% 12.8
Predicted 50.300

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