Multivariate Operating Speed Forecasting Model Based on the Geometric Elements of Two-Lane Highways

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***Abstract*—Operating speed forecasting models for two-lane highways have been used since the mid 1950s. Most of those models use the radius of curvature as the only independent variable. Although models that attempt to include other important geometric elements (longitudinal grade, curve side, road width, etc.) present higher coefficients of determination (R2), most times they turn out not to be statistically valid. That fact results from the correlation between the geometric variables of the design stage, characterizing their classification as independent variables and inflating the model. The use of multivariate analysis, using principal components allows the transformation of the geometric variables into orthogonal components in relation to each other, i.e., independent from each other. Using this tool, this paper presents an operating speed forecasting model using the geometric elements (radius, curve side, longitudinal grade) for two-lane highways in Brazil. The paper also presents a sensitivity analysis of the proposed model.**

***Index Terms*—geometric consistency, operating speed, road safety**

I. Introduction

The speed practiced on a highway, called operating speed, is the result of the degree of comfort and safety that drivers experience when driving their vehicle on a highway. This single variable, the operating speed, synthetizes the relations among the three main agents of the road system: road, driver and vehicle. Road safety results from how these agents relate to each other. Inconsistencies among these agents are seen as detrimental to road safety.

The analysis of geometric consistency is aimed at identifying the road segments where the standard of road use is not according to plan. One example of inconsistency is when the operating speed of a road segment is significantly higher than its design speed. In that situation, drivers believe that it is possible to drive safely and comfortably at a higher speed than the road's design speed.

Geometric consistency analysis has been used as a tool to assess design and operating problems in existing roads and in roads under implementation. The *Federal Highway Administration* – FHWA recommends the use of this type of analysis to assess road safety in two-lane highways. The models used in the analysis of geometric consistency are adjusted for the cultural conditioners of drivers, vehicles and roads in the United States, reflecting that country's reality. Therefore, direct application of the IHSDM – *Interactive Highway Safety Design Model* software [1] in two-lane highways in Brazil is not recommended.

This study is aimed at conceiving and assessing an operating speed forecasting model adjusted for two-lane highways in Brazil. To achieve this objective, the study uses multivariate analysis, based on principal components.

This article is organized as follows: section 2 presents a summary of the main references on operating speed, section 3 discusses geometric consistency and section 4 presents the development of the model proposed for the estimation of V_{85} in the middle of the horizontal curve. Finally, sections 5 and 6 present, respectively, the analyses of the model proposed and the conclusions.

II. Operating Speed

Operating speed results directly from the driver, vehicle and road relationship. In the other hand, the design speed, is used in the dimensioning of different road elements. Some examples of those elements are superelevation, super-width and sight distances.

Different studies point to a cause-effect relation between speed, crash rates and their severity. In their studies about the highways of the state of Virginia, US, Reference [2] consider it possible to generate models that relate crash rate to speed and vehicle flow and to the geometric characteristics of roads. In a previous study of roads in [3] already presented models to estimate the

Manuscript received November 15, 2012; revised February 27, 2013.
This work was supported in part by CNPq.

doi: 10.12720/jtle.1.2.97-103

operating speed and accident rate as a function of the degree of curvature and road width.

The development of operating speed forecasting models based on the geometric features of roads has been recurrent since the mid 1950s. Operating speed forecasting models for horizontal curves have been evaluated by [4]-[16]. Others, including [17]-[19], sought to establish correlations for predicting operating speed in tangents.

The Federal Highway Administration [1] presents a series of operating speed forecasting models. Four of those models, generated from data collected in 176 two-lane highway segments, estimate the operating speed as a function of the horizontal curve radii for different longitudinal grade intervals, as shown on Table I.

TABLE I. MODELS: V85 FUNCTION PLANIMETRIC RADIUS AND LONGITUDINAL GRADE

longitudinal grade	Model	R^2	Equation
-9% ≤ i < -4%	$V_{85} = 102{,}10 - 3077{,}13/R$	0.58	(1)
-4% ≤ i < 0%	$V_{85} = 105{,}98 - 3709{,}90/R$	0.76	(2)
0% ≤ i < 4%	$V_{85} = 104{,}82 - 3574{,}51/R$	0.76	(3)
4% ≤ i < 9%	$V_{85} = 96{,}61 - 2752{,}19/R$	0.53	(4)

V_{85}:operating speed [km/h]
R:radius of curvature [m]
Source: Fitzpatrick (2000)

The operating speed is defined as the limit speed performed by 85% of drivers on a road section.. Hence, operating speed is also denominated V_{85}. The V_{85} can be obtained by directly measuring speeds at different road segments. The V_{85} can also be obtained by forecasting models based on the geometric elements of the road. The advantages of using the latter procedure include the possibility of estimating the V_{85} of roads that are in the design stage and the fact that it is much more cost effective than carrying out a field survey. The use of the geometric elements of the road as explanatory variables for the variability of the V_{85} has proven to be appropriate. It is possible to obtain coefficients of determination close to 0.7 [20], [1].

III. GEOMETRICAL CONSISTENCE

The operating speed estimated by the forecasting models is used as a fundamental element in the analysis of geometric consistency. The concept of geometric consistency analysis proposed by Reference [20] states that the road must have a balance between its geometric elements along all of its extension. This balance is crucial for the establishment of a standard of use by drivers. If this standard is not offered throughout the road, it produces a situation of violation of drivers' expectation [21]. At that moment it generates a situation of risk to road safety. Hence, it is important to offer highways with the best possible harmony among its geometric elements.

The method of analysis of road consistency proposed by the Federal Highway Administration in the IHSDM software – *Interactive Highway Safety Design Model* [1], establishes two criteria of classification of the road according to its safety. Safety criterion I, also denominated design consistency, assesses the difference between operating speed and design speed. Safety criterion II, or operating speed consistency, evaluates the difference between operating speeds in successive sections.

In both analysis, differences of up to 10 km/h are considered acceptable and, in this situation, the designs are considered "good" in terms of their geometric consistency. When the differences are between 10 and 20 km/h, the design is considered "fair", indicating the need for intervention. Road designs are classified as "poor" when the difference is higher than 20 km/h. In that case, there are serious road safety problems.

IV. THE MULTIVARIATE OPERATING SPEED FORECASTING MODEL

The experimental design that provided an operating speed forecasting model based on the geometric elements of two-lane highways in the state of Rio Grande do Sul, observed a series of criteria, as follows:

- Identification of the sample interval: 60 curves were analyzed, measured in both directions (left side and right side of each curve), totaling 120 sites, with planimetric radii intervals between 50 and 1000 meters and longitudinal grades between -8% and 8%.
- Determination of the sample size per curve: for a standard deviation of 8.5 km/h, the value assigned to two-lane highways [22], a confidence level of 95% (K = 1.96), an admissible error for the estimate of km/h and a correction constant for the 85 percentile (U = 1.04), the minimum sample size obtained was 27 data of spot speed per site, i.e, for statistical purposes, a minimum of 30 data per site with verification of the standart deviation.
- Type of vehicle: from all the spot speed data collected, this study considered only those of passenger cars in free-flow.
- Collection method of spot speed data: the long-base method, [23], to obtain punctual speeds, due to easy access to the equipment and straightforward collection procedures.
- Collection method of topographic data: the identification of the main characteristic elements of the curves (planimetric radius and longitudinal grade) was done through a topographic survey. The surveying method used is called tacheometric survey, and it was chosen due to the fact that this method requires a team of no more than two individuals.
- Considerations about the segments under study: the development of an operating speed model based on the geometric parameters of two-lane highways should eliminate or reduce the interference of other factors outside the research study. Hence, conditioners were established for the selection of the segments, such as, for instance:

free-flow, minimal upstream alignment, inexistence of close intersections, inexistence of objects nearby the road, pavement and weather.

- Data on the highways in the study: this study was developed using four highways registered in the Rio Grande do Sul State Highway System [24]. All four highways are two-lane roads and their service level is higher than or equivalent to level C (mean speeds equal to or close to the free-flow speed). The highways selected were the RS-020 (located in a rolling region), the RS-115 (rolling to mountainous), the BR-116 (mountainous) and the RS-040 (level).

From the 120 sites surveyed, 26 were excluded because they presented problems in the sample size or in the minimal intertangent. The data used by the study were as follows: 30 data from RS-020, 19 from RS-115, 22 from BR-116 and 23 from RS-040. Hence, a total of 94 data were used in the development of the model and its validation.

A. Analysis of Variables

The geometric elements present in the database and considered in this study were divided into two groups. The first group, consisting of 71 elements (75% of the total), was used to create the model. The 23 remaining elements (25%) were separated for validation.

1) Analysis of the V85 as a Function of the Variable Radius

Equations 1 to 4, presented on Table 1, suggest linear regression models based on the horizontal radius, presenting the operating speed as its inverse function. Fig. 1a indicates, in a graphic, the direct relation between operating speed and radius, while Fig. 1b presents the inverse relation. It is possible to observe, through the tendency lines, the best adjustment of the line in Fig. 1b. This fact is confirmed by comparing the values of the coefficients of determination in Fig. 1.

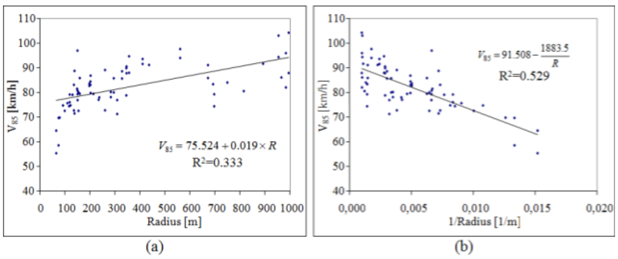

Figure 1. Operational speed as a function of the radius (a) and as inverse function of the radius (b).

2) Analysis of the V85 as a Function of the Longitudinal Grade

The models proposed by the FHWA [1] suggest the influence of the gradient of the longitudinal grade on operating speed. An analysis of equations 1 to 4 shows that for infinite radius, the operating speeds for longitudinal grades between 0% and -4% and between 0% and 4% are 105.98 and 104.82 km/h, respectively, and that the speed drops in the more critical intervals of ascending or descending grades (96.61 and 102.10 km/h). That behavior characterizes speed variability as a function of the absolute values of the longitudinal grade variability. In fact, an analysis of Fig. 2, shows that it is impossible to explain the variability based on the independent variable longitudinal grade, while it shows a relationship between the variability of operating speed and the absolute values of longitudinal grades.

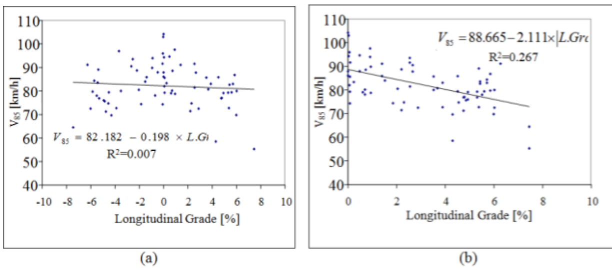

Figure 2. Operating speed as a function of the longitudinal grade (a) and of its absolute value (b).

That behavior, presenting higher speeds for gentler slopes, can also be observed in the models proposed by FHWA [1]. Fig. 3 shows that the highest operating speeds occur in the 0% to -4% and from 0% to 4% ranges. The other ranges present lower speed values.

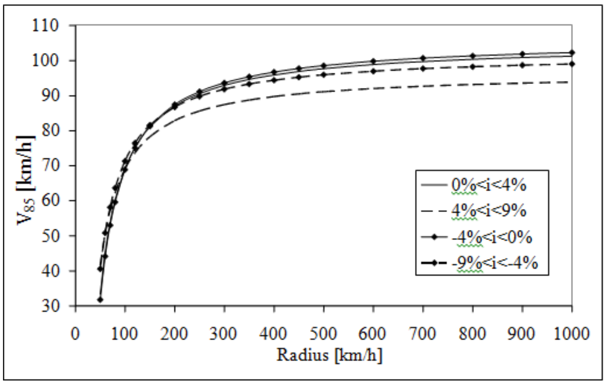

Figure 3. Models V85 as a function of the radius for grade intervals.

The model for grade intervals between 4% and 9% is inferior to the others. In this situation, there is a drop in vehicles' performance, particularly in heavier and less powerful vehicles. The analysis of the influence of the longitudinal grade on speed determined that it should be broken down into two variables. The first one identifies the influence of the absolute value of the longitudinal grade, the second variable differentiates between ascending and descending slopes.

3) Analysis of the V85 as a Function of the Curve Side

Among the 71 data used in the development of the model, 34 were of right curves and 37 of left curves. The analysis of speed behavior, in the two different models produced the mean values of 83.50 km/h and 80.98 km/h and standard deviations of 1.675 km/h and 1.420 km/h, respectively. The analysis done through SPSS (T-TEST) yields a t = 1.156, which is below the critical t, for 69 degrees of liberty and a level of signification of 1.997.

Thus, there is nothing against considering that there is no significant difference between the two groups.

Although the curve side variable did not present statistical justification to be included in the model, this study has chosen to consider it relevant. In practice, we can observe that left curves (external) give the driver the perception of greater insecurity, influencing his behavior in relation to speed.

B. Development of the Forecasting Models for the V85

This paper proposes a multivariate model to forecast the V_{85} based on a set of geometric elements. The geometric elements available for analysis were: (i) radius planimetric, (ii) gradient of the longitudinal grade and (iii) side of the horizontal curve. As a reference for the analysis, it also proposes a model for the V_{85} as a function of the planimetric radius.

1) Model Operating speed as a function of the planimetric radius

The great majority of operating speed forecasting models uses as explanatory variable the inverse of the planimetric radius. In the analysis performed in this study, it was possible to obtain the model presented in Equation 5. The data utilized were the same as those used by Reference [25], but considering only passenger cars.

$$V_{85} = 91.508 - \frac{1883.440}{R} \quad (5)$$

where:		P-Value
V85 = operating speed [km/h]	Constant	0.0000
R = radius of curvature [m]	1/Radius	0.0000

R2 = 0.529

2) Model operating speed as a function of the geometric elements

The main geometric elements of a highway (radius, longitudinal grade, etc.) present threshold values (minimum and maximum) established based on road class and the topography, according to its design speed. In this situation there is multicolinearity among the geometric elements defined as the “independent” variables of the model.

In the generation of multiple regression models, the multicolinearity of the variables results in the following problems:

- The variability of predictions obtained by the model is inflated;
- The variability of the dependent variable explained by each independent variable cannot be determined independently;
- The presence of an independent variable affects the coefficients of the other independent variables that are correlated to it.

To eliminate the problems resulting from the multicolinearity, multivariate analysis was used. The principal components result from the transformation of the variables, based on axes that present greater variance. Another peculiar characteristic is the orthogonality between the variability axes. That orthogonality characterizes the independence between the main different components.

Hence, starting from the variables related to the curve (1/radius and dummy side) and related to the longitudinal grade (slope ou ramp and dummy upgrade), it is possible to obtain totally independent main elements and possible to be used in a statistically valid multiple regression models.

The multiple regression was done, using operating speed as a dependent variable, and, as independent variables, the four principal components (PC) generated in the multivariate analysis. Hence, Equation 6 was obtained with the respective angular coefficients β for each PC.

$$V_{85} = 91.154 - 1485.020 \times PC1 + 232.379 \times PC2 + 133.267 \times PC3 - 1517 \times PC4 \quad (6)$$

where:		P-Value
V85 = operating speed [km/h]	Constant	0.0000
PC1 = principal component 1	PC1	0.0000
PC2 = principal component 2	PC2	0.0000
PC3 = principal component 3	PC3	0.0000
PC4 = principal component 4	PC4	0.0000

R2 = 0,547

As well as having a coefficient of determination higher than Equation 5, Equation 6 has statistically significant independent variables for a 99% confidence level.

The only disadvantage of the generated model is that it does not directly relate the depended variable, V_{85}, with the original independent variables. This disadvantage can be offset by multiplying the angular coefficients (β) of the principal components by the standardized weights, resulting from the multivariate analysis. The total of these values for each original value generates the angular coefficients of the rewritten model, as shown in Equation 7 [26].

$$V_{85} = 93.154 - \frac{1666.172}{R} - 1.187 \times L - 0.465 \times |I| - 1.343 \times A \quad (7)$$

where:
V85 = operating speed [km/h]
R = radius of curvature [m]
|I| = gradient of the longitudinal grade - absolute value [%]
L = dummy side [1 - left, 0 – right]
A = dummy upgrade[1 – upgrade, 0 – downgrade or level]
R2 = 0.547

Finally, the model expressed by Equation 7 does not present residuals, with the variance pattern as a function of the independent variables, and can, therefore, be considered valid.

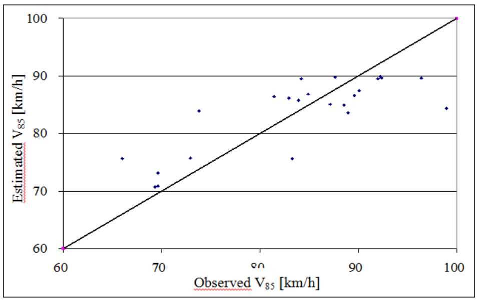

Figure 4. Observed V85 versus estimated V85.

C. Validation and Performance Measure

To validate the model and obtain performance measures 23 data of V_{85} speeds were used. In Fig. 4 the values of the V_{85} observed on the field are plotted in the X axis and the V_{85} estimated by the model are plotted in the Y axis.

Table II presents the performance measures resulting from the data used in the conception of the model and in the data used for its validation. The measures presented are: ME – mean error, MAE – mean absolute error, MSE – mean square error, MPE – mean percentile error, MAPE – mean absolute percentile error, $\chi 2$ – chi-squared and $\chi 2_{critical}$ – critical chi squared.

TABLE II. PERFORMANCE MEASURES OF THE MODEL AND THE VALIDATION

	Model	Validation
ME	-1.20	0.23
MAE	4.93	4.42
MSE	42.15	30.28
MPE	-2.08%	-0.26%
MAPE	6.11%	5.32%
$\chi 2$	35.464	8.427
$\chi 2_{cr\ fico}$	90.531*	33.924*

* *$\chi 2_{cr\ fico}$ obtained for a signification level of 5% and 70 degrees of liberty for the model and 23 for the validation*

It is important to point out that the values obtained in Table 2 are according to expectation. The mean absolute error values of the model and the validation fall into the range observed in the four models adopted by the FHWA [1], which use radius as dependent variable for different grade ranges, with mean absolute error between 3.735 and 6.13. The chi-square value lower than the critical ones indicate that there is no significant difference between observed and the estimated values.

V. ANALYSES

A. Sensitivity Analysis

The sensitivity analysis of the estimated model for forecasting $V_{85,}$ shows that, for every increase in the values of the independent variables, there is a decrease in the value of the dependent variable (V_{85}). That results from the negative sign of the coefficients of the independent variables. This construction was aimed at establishing the highest possible linear coefficient, i.e., the highest V_{85} for the least restrictive conditions of radius, curve side and longitudinal grade. The value obtained for the linear coefficient was 93.154 km/h, the maximum limit of the V_{85} estimated by the model.

The sensitivity analysis of the 1/radius variable reveals that it is the greatest contributor to the model. A 50-meter radius causes a reduction of 33.323 km/h in the V_{85}, considering the maximum limit estimated by the model for that speed. Radius values below 50 meters were not considered, as they are below the minimum limit established by the guideline for Class III highways (radius 50.580 meters).

The larger the radius, the smaller its contribution to the reduction of the V_{85}. In the case of infinite radius (tangent section) its contribution is null, which results, disregarding all other variables, in a maximum V_{85} of 93.154 km/h.

The sensitivity analysis of the dummy variable (1 for the left and 0 for the right) shows that when driving on a left curve, with a 0% longitudinal grade, there is a reduction of 1.1872 km/h in the V_{85}. For right curves the V_{85} remains unchanged, according to the estimated model. In this study, it was not possible to assess if the influence of the V_{85} on left curves and right curves presents any significant variances as a function of the radius (effects of 2^{nd} order).

The longitudinal grade is a variable that some forecasting models consider directly or indirectly. Its indirect inclusion takes place through the formulation of different equations, by grade range, as proposed by the FHWA [1]. In the proposed model, it was decided to break the longitudinal grade variable in two: the absolute value of the grade and the dummy variable upgrade (1 for upgrade and 0 for downgrade or level).

A grade with absolute value of 0% does not have any influence on the $V_{85.}$ For a variance of 1% in the absolute value of the grade, for both upgrade and downgrade, there is a variance of 0.465 km/h in the V_{85}. For Class III highways in mountainous regions, the guidelines allow grades of up to 8% in short segments (150 meters). In this case, the reduction in the V_{85} is 3.723 km/h.

Fig. 5 presents the V_{85} for left curves, with grades of 0% (level), -4% e -9% (downgrade), 4% and 9% (upgrade), as a function of the radius. The plotted curves indicate the effect of the grade on the V_{85}.

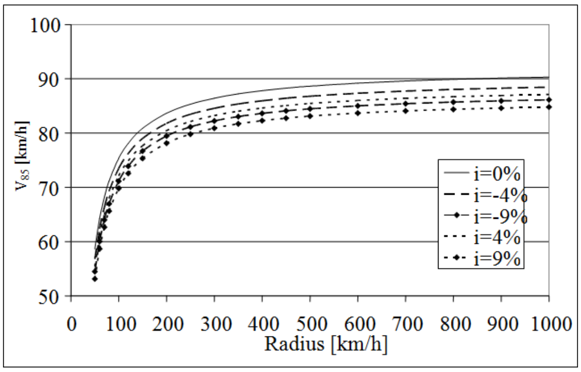

Figure 5. Estimated V85 for the left side, grade range

Although the values –9% and 9% exceed the limit indicated in the guidelines, they were used in this study to facilitate the comparative analysis of the proposed model with the FHWA's models [1].

The dummy variable was introduced in the model in order to introduce the performance drop effect that vehicles present on upgrades. It is important to highlight that the proposed model was conceived for passenger cars, which do not present a significant speed reduction, as is the case with heavy trucks. The sensitivity analysis of this variable indicates that, on upgrades there will be a reduction of 1.343 km/h in the V_{85}, regardless of the degree of longitudinal grade.

B. Comparative Analysis

For the comparative analysis between the proposed model and equations 1 to 4 in the FHWA model *(1)* the four charts in Fig. 6 were produced.

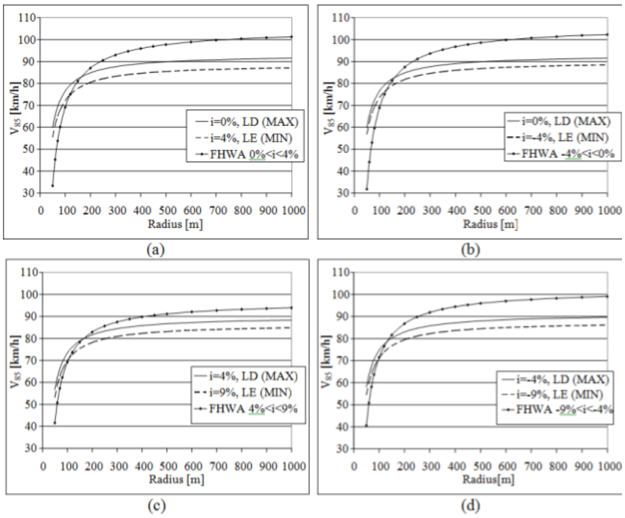

Figure 6. V85 proposed versus FHWA model (Fitzpatrick, 2000), by longitudinal grade ranges (a) – grade 0 to 4%, (b) – -4 to 0%, (c) – de 4 to 9% and (d) – from -9 to -4% .

For each one of the equations 1 to 4 of the FHWA model [1], with the V_{85} plotted in a continuous line with dots, two curves were generated characterizing the minimum and maximum values for the longitudinal grade range and curve side of the proposed model. Thus, Fig. 6a presents, in a continuous line, the maximum values of the V_{85} as a function of the radius of curvature for the 0% grade and right curves. In the same chart, the broken line shows the minimum values (4% grade and left curve). The area between the continuous line and the broken line is the area of the possible V_{85} of the proposed model for the longitudinal grade range, the radius and the side of the curve indicated.

The charts in Fig. 6 show that the V_{85} estimated by the FHWA model [1] are always higher than the possible values of V_{85} estimated by the proposed model. Although all the curves present the same functional form (asymptotic with a maximum value), the ones in the proposed model are less elastic. It is possible to perceive that the maximum speeds, for large radii, in the proposed model are significantly lower than the ones in the FHWA model [1]. On the other extreme, for very small radii, this relationship is inverted. This pattern of behavior, already verified by Reference [25], indicates that although typical Brazilian drivers do not drive at "high speed" in straight road sections, they present a less elastic behavior in terms of reducing speed in more critical radius situations that highways present [25].

VI. CONCLUSIONS

The estimate of an operating speed forecasting model based on a multivariate approach to the geometric elements of the road allowed a series of analyses and conclusions, as follows:

- The method proposed by the FHWA [1] uses ten different V_{85} forecasting models, according to different geometric characteristics of the segment analyzed. The use of different models can generate inconsistencies (steps) in the estimates of operating speeds on their limits of application. The proposed model is not subject to those discontinuities in its estimates;
- The multivariate approach using principal components is an important tool in the construction multiple linear regression models when the variables taken as independent present correlations with each other, as occurred in this study.
- The independent variable radius is the one with the greatest capacity to explain the variability of the dependent variable V_{85}. This study shows that the use of the radius in its inverse form allows 52.91% of the V_{85} to be explained;
- The inclusion of the geometric elements analyzed (side of the curve and longitudinal grade) in the model was only possible thanks to the application of multivariate analysis, using principal components. However, the inclusion of those elements in the model had a small impact on the coefficient of determination. That went from 52,91% to 54,70%.
- The sensitivity analysis identified the value of 93.15 km/h as the maximum limit of the V_{85} estimated by the model, in the condition of infinite radius (tangent section) and longitudinal grade equal to 0% (level);
- The model presents a significant reduction in the V_{85} for radii smaller than 250 meters. Radii of 1000 meters or more present reductions lower than 2 km/h;
- The contribution of the side of the curve to reduce operating speed is close to 1.2 km/h. That reduction is estimated only for left curves (external);
- The longitudinal grade contributes with 0.5 km/h for each 1% gradient. In upgrades, approximately 1.3 km/h must be added, as a result from vehicle performance drop;
- The model generated, compared with the FHWA model, presents a limited degree of elasticity. While equations 1 to 4 give V85 values between 33 km/h and 103 km/h for radii between 50 and 1000 meters, the amplitude of the proposed model ranged between 55 km/h and 92 km/h;

The proposed model was considered satisfactory. Its capacity to explain operating speed, based on different easily obtained geometric elements, reached values close to those seen in equations 1 to 4 of the FHWA model [1]. It should be highlighted that the model generated in this study is adjusted for the conditions of geometric design, vehicles and culture found in the south of Brazil.

Future studies can be undertaken using the proposed model as a tool for analyzing the geometric consistency of highways. Based on the V85 estimated by the model (potential operating speed, i.e., the one that can be achieved without prior restrictions), and adding acceleration and de-acceleration factors, it will be possible to expand the analysis of the effective V85 to an entire road segment.

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