SPEED PREDICTION MODELS FOR TRUCKS ON HORIZONTAL CURVES OF TWO-LANE RURAL ROADS

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ABSTRACT

Road safety is closely related to geometric design consistency, which is usually assessed by examining operating speed. Most of consistency models only consider passenger car speeds, even though the interaction between passenger cars and heavy vehicles plays a pivotal role on road safety. This is due to the few models to estimate heavy vehicle speeds.

This study aims to develop speed prediction models for heavy vehicles on horizontal curves of two-lane rural roads. To do this, continuous speed profiles were collected by using Global Positioning System (GPS) tracking devices on eleven road sections. As a result, truck speeds were analyzed on 105 horizontal curves.

The results showed that the radius of the horizontal curve and the grade at the point of curvature have a great influence on heavy vehicle speeds. To this regard, vertical alignment only has a significant effect on truck speeds developed along upgrades. In addition, different trends were identified for loaded and unloaded trucks.

Several speed models were calibrated for both loaded and unloaded trucks. As a result, heavy vehicle speeds were adversely affected by grades greater than 3%. This phenomenon was larger for loaded trucks than for unloaded ones.

Finally, the calibrated 85th and 15th percentile speed models were compared with those developed previously. As a conclusion, the use of the proposed models in this study was recommended on Spanish two-lane rural roads due mainly to the different characteristics of heavy vehicles around the world.

Keywords: speed model, operating speed, trucks, two-lane rural roads, geometric design

INTRODUCTION

Road safety is one of the major concerns in our society. In fact, around 1.2 million people die and 50 million are injured in road crashes every year *(1)*. To this regard, road accidents are mainly caused by three concurrent factors: infrastructure, vehicle, and human factors.

Specifically, the interaction between the infrastructure and human factors has been thoroughly studied in recent years through geometric design consistency, which can be defined as how driver's expectations and road behavior relate. In this way, a consistent road minimizes unexpected events to road users while driving along it, whereas an inconsistent road might present numerous surprises on drivers, leading to anomalous behavior and increasing the likelihood of crash occurrence.

The most commonly used methods to evaluate geometric design consistency are based on operating speed (V_{85}). This speed is defined as the 85th percentile of the distribution of speeds selected by drivers under free-flow conditions with no environmental restrictions. This speed can be estimated by means of operating speed models. Although there are a lot of models which allow estimating the operating speed for passenger cars on two-lane rural roads, the existing models to predict the operating speed for heavy vehicles are very few. For this reason, most of the consistency models are only based on the operating speed profile of passenger cars.

In addition, heavy vehicles should be better integrated into highway design guidelines. Although the ASSTHO Green Book takes into account them for pavement design, climbing lanes, superelevation rate, and speed deceleration on upgrades and downgrades, Spanish highway design guideline only considers them for climbing lanes and pavement design. However, the interaction between both passenger cars and heavy vehicles plays a pivotal role on road safety, mainly on two-lane rural roads with a large percentage of heavy vehicles *(2)*. Therefore, not considering heavy vehicle speeds might lead to inconsistent geometric designs.

Some authors have studied this phenomenon through the speed difference between passenger cars and heavy vehicles. According to Harwood et al. *(3)*, this speed difference might cause inconsistencies on vehicle operation along upgrades. Likewise, Leisch and Leisch *(4)* suggested that this speed difference should be limited to 15 km/h.

On the other hand, several research have been focused on the calibration of operating speed models for heavy vehicles. Two types of models can be distinguished, those based on speed data collected on rural roads and those based on dynamic and cinematic performance.

Regarding the first ones, Misaghi and Hassan *(5)* analyzed the influence of several geometric variables of horizontal curves, such as the radius or the grade, on heavy vehicle speeds. Speed data were collected using electronic counter–classifiers on 20 horizontal curves of two-lane rural roads. As a result, two speed models were proposed to estimate the 85th percentile speed at midcurve with the radius of the horizontal curve as the explanatory variable. In addition, statistically significant differences between passenger car speeds and heavy truck speeds were identified, but not between passenger car speeds and light truck speeds.

Jacob and Anjaneyulu *(6)* studied the operating speed of different types of vehicle (passenger cars, motorcycles, buses, and trucks) on 152 horizontal curves with grades between -2% and +2%. As a conclusion, significant differences between the speeds and speed reductions developed by the different types of vehicle were found. Hence, separate models were developed to analyze the influence of geometry on the speeds of the different types of vehicle. The results indicated that the radius and length of the horizontal curve had a significant influence on operating speed. The greater the radius or length of the horizontal curve, the greater the speed differences between the different types of vehicle.

However, most of the researchers concluded that while passenger car speed profiles can mainly be based on horizontal alignment, heavy vehicle speed profiles depend on both horizontal and vertical alignment. Therefore, the analysis of the operating speed differences between passenger cars and heavy vehicles should be carried out considering three-dimensional (3D) geometric effects. To this regard, Leisch and Leisch *(4)* developed a speed profile by combining the speed profile only considering the horizontal alignment (assuming a level grade) and that profile only considering the vertical alignment (assuming no restrictions on the horizontal alignment).

Likewise, several regression models were developed by Donnell et al. *(2)* to predict 85th percentile speed of heavy vehicles on horizontal curves. These models were calibrated using a combination of field data collected on 11 horizontal curves of two-lane rural roads and simulated data by means of TWOPAS. In this way, it was found that an increase of the radius of the horizontal curve and the length of the approach tangent was associated with greater operating speeds at the point of tangency. In addition, a high grade of the approach tangent was associated with a lower operating speed at this same location.

Another study based on the horizontal and vertical alignments was developed by Gibreel et al. *(7)*. In this case, speed data were collected for all types of vehicle under free-flow conditions on 9 horizontal curves combined with a sag curve and 10 horizontal curves combined with a crest curve. The results showed that several parameters significantly affect the operating speed: radius of the horizontal curve, deflection angle of the horizontal curve, horizontal distance between the point of horizontal intersection and the point of vertical intersection, length of the vertical curve, grade, and superelevation rate.

On the other hand, Saifizul et al. *(8)* studied the influence of the size and weight on heavy vehicle speeds. To this regard, important speed differences were found when vehicles were significantly different in size. In addition, when vehicles were almost similar in size and only differed in the number of axles, the Gross Vehicle Weight (GVW) was the most influential factor. If GVW was lower than 20 t, the speed decreased as the weight decreased. By contrast, the speed remained without variation when GVW was greater than 20 t.

Besides, other heavy vehicle speed profile models have been developed on upgrades based on dynamic and cinematic performance *(9-12)*. These models were mainly used for the study of ascending lanes for heavy vehicles. These speed models depend on the grade, the vehicle weight-to-power ratio (WPR), the resistance of the air, pavement characteristics, rolling resistance coefficients, and the coefficient of friction.

Summarizing, few operating speed models for heavy vehicles have been calibrated. In addition, most of these studies used spot speed data collected on a low number of horizontal curves and presented a large variation in model form, explanatory variables, and regression coefficients. This might be due to differences in driver behavior, mechanical characteristics of the vehicles, and road geometry. Thus, a single model is not universally accepted.

The present research analyzes truck speeds on horizontal curves of two-lane rural roads based on continuous speed profiles collected using Global Positioning System (GPS) tracking devices. The main advantage of this method is a large amount of continuous speed data that can be collected without significant influence on drivers.

OBJECTIVE AND HYPOTHESES

The objective of this study is to analyze the influence of road geometric design on heavy vehicle speeds and develop speed prediction models on horizontal curves of two-lane rural roads. This research does not only focus on the evaluation of the operating speed, but also analyzes 15th percentile speed, since the low percentiles encourage the emergence of traffic conflicts between passenger cars and heavy vehicles.

The research is based on two hypotheses. The first one is that road grade, which does not influence on passenger car speeds, produces lower heavy vehicle speeds on upgrades. Likewise, the second hypothesis is that the speed difference between heavy vehicles with similar weight is very low as, despite passenger car speeds are mainly influenced by the driver, heavy vehicle speeds are significantly influenced by the heavy vehicle engine performance or the weight-to-power ratio (WPR).

METHODOLOGY

This research was based on continuous speed data collected through Global Positioning System (GPS) tracking devices. First, GPS devices were lent to three transport companies, which equipped their heavy vehicles with these devices. Next, the transport companies gave back the devices and the speed data were filtered and processed. In addition, information about the use of each GPS (day, time, and type of heavy vehicle) was also reported by the transport companies. The geometry of the two-lane rural roads was recreated by means of the methodology proposed by Camacho-Torregrosa et al. *(13)*. Finally, different regressions models were calibrated based on the geometric characteristics of the horizontal curves to predict heavy vehicle speeds.

DATA COLLECTION

Speed data were collected between May 2015 and July 2015 in working days under dry weather conditions. Heavy vehicles of three transport companies were equipped with 1Hz pocket-sized Global Positioning System (GPS) tracking devices. The accuracy of these GPS devices was 2.5 m. However, this accuracy is mainly composed by a general bias (common to all measurements) and a minimum random error. Actually, the bias can be addressed through moving all trajectories (it does not affect accuracy), while the second error is minimum (millimeters), thus being very easy to address.

Heavy vehicles performed round trips, loaded in one direction and unloaded in the other direction. All heavy vehicles were 5 axles, single trailer. The weight-to-power ratio (WPR) ranged between 35 and 54 kg/kW for unloaded trucks, being its average value 43 kg/kW. However, the average WPR increased to 120 kg/kW for loaded trucks.

The results of data collection were a database of vehicles location in a latitude-longitude-altitude-heading direction-time-date format, at a 1-second pace.

Collected data were transformed to Universal Transverse Mercator (UTM) coordinates and filtered and processed to obtain individual continuous speed profiles *(14)*. After that, free-flow conditions were checked *(15)*. The used test is based on the hypothesis that every single driver behaves in a particular way, approaching their individual speed profile to a certain speed percentile. Therefore, for each individual speed profile, non-free-flow road sections were associated with sudden changes in its usual operating percentile.

After removing non-free-flow sections for every single driver, 85th and 15th percentile speed profiles were obtained. From these profiles, the minimum speed and the speed at midcurve were identified for each horizontal curve.

Additionally, eleven two-lane rural road segments were identified from the path of the selected heavy vehicles (Table 1). All road segments are located in the Valencian region (Spain). The lane width ranged from 3.0 to 3.5 m, while the shoulder width varied from 1.0 to 1.5 m. The horizontal alignment of these two-lane rural road segments was recreated using an algorithm based on the heading direction *(13)*. Additionally, the vertical alignment was obtained by means of the geometric road design software Civil 3D using LIDAR data provided by PNOA (National Plan for Aerial Orthography) with a root mean square error of 20 cm in height *(16)*.

TABLE 1 Parameters of the Road Segments

Road	Name of the Segment	Length (m)	Grade Range (%)
CV-425	Buñol - Alborache	1,956	-8 +6
CV-425	Alborache - CV-429	752	-3 +6
CV-425	Macastre I - Macastre II	1,419	-5 +2
CV-425	Macastre II - CV-580	11,996	-9 +11
CV-425	La Matrona I - La Matrona II	5,836	-12 +12
CV-345	Villar del Arzobispo - Higueruelas	7,215	-5 +8
CV-600	Xávita - Fenollet	2,685	-2 +2
CV-610	Genovés - Cuatretonda	7,304	-8 +10
CV-610	Cuatretonda - Llutxent	2,686	-3 +10
CV-608	Llutxent - Planta	1,660	-8 +8
CV-610	Llutxent - CV-60	5,685	-5 +6

Finally, the selection of horizontal curves was carried out by means of the analysis of the speed profiles. To this regard, only horizontal curves that presented a significant speed reduction were selected, i.e., those that acted as a geometric control on drivers (Figure 1). As a result, 105 horizontal curves were considered in this research.

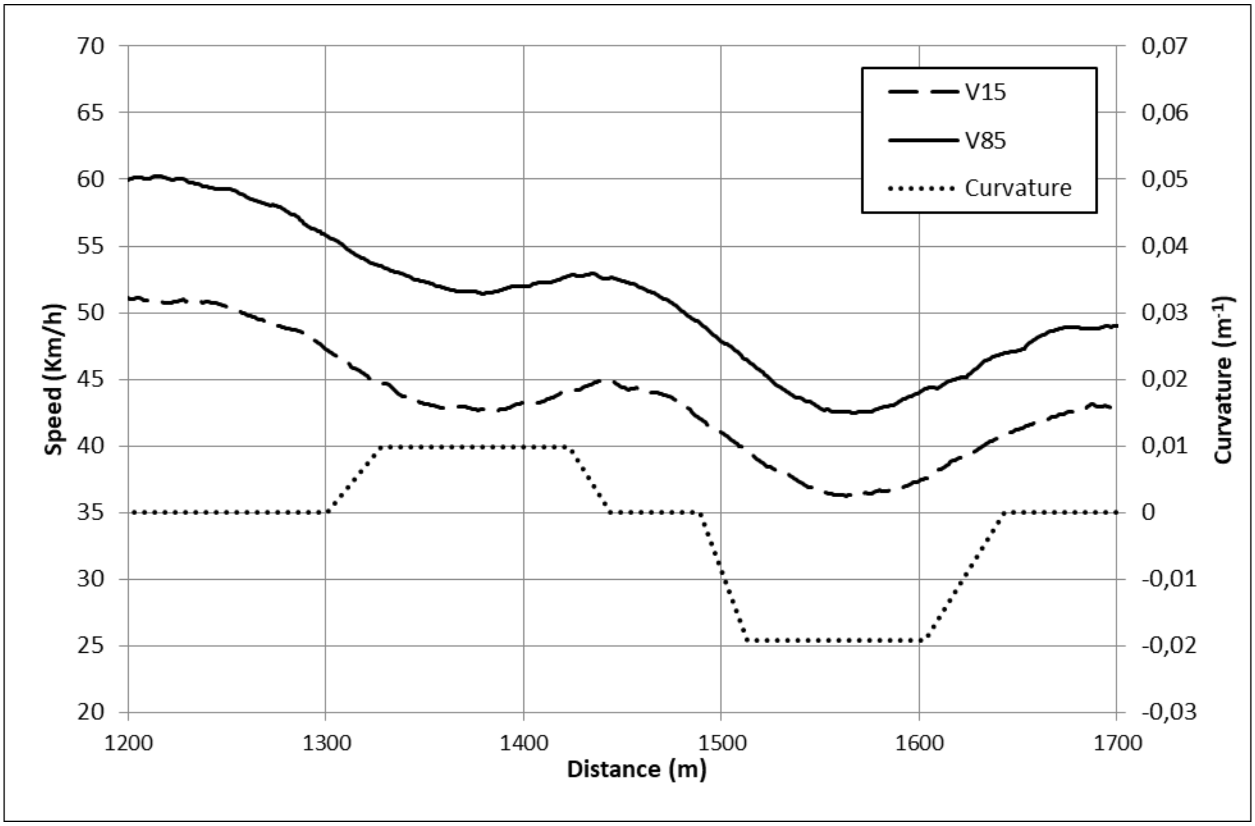


FIGURE 1 Horizontal curve selection.

Table 2 shows a statistical summary of the geometric variables of the selected horizontal curves. Regarding this, the Curvature Change Rate (CCR) was calculated as follows:

$$\text{CCR} = \frac{\gamma}{L} \quad (1)$$

where CCR = curvature change rate (gon/km); γ = deflection angle of the curve (gon); and L = curve length (km).

TABLE 2 Statistical summary of geometric variables at horizontal curves

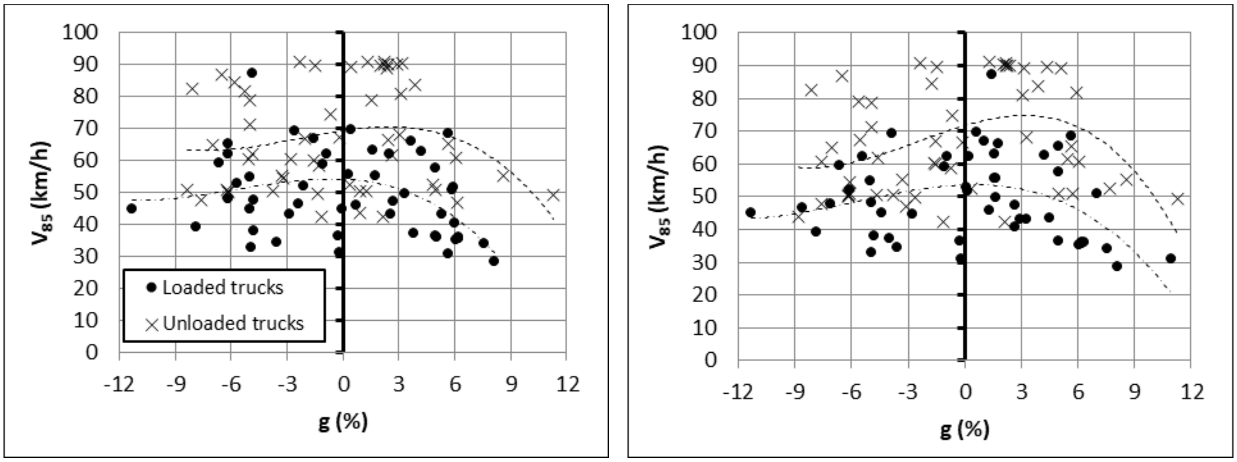
Variable	Notation	Minimum	Maximum	Mean	Standard deviation
Radius (m)	R	18.45	1,178.36	167.43	228.52
Length of curve (m)	L	32.00	250.00	94.50	47.35
Deflection angle (gon)	γ	3.94	159.82	51.57	37.46
Length of preceding tangent (m)	L_t	7	1359	194	214
Curvature Change Rate (gon/km)	CCR	41.51	2,464.65	618.21	449.34
Grade (%)	g	-11.31	11.31	-0.04	4.68

Regarding the vertical alignment, a preliminary analysis was performed to evaluate the influence of the grade on speed. For this, the grade at different points of the horizontal curve (at the point of curvature, at midpoint and at the end) and the average grade were studied (Figure 2). It should be noted that the grade at the point of curvature coincided with the grade along the preceding tangent. Only a few tangents presented different grades along them. In this case, the grade at the final part of the tangent was considered.

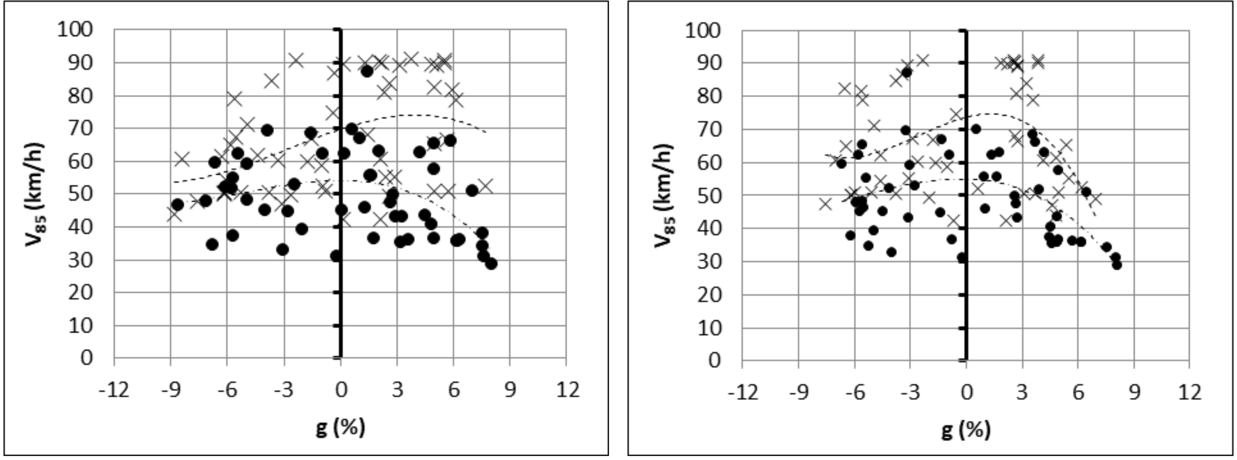
It was observed that the grade at the point of curvature and the grade at midpoint could better explain the phenomenon (Figure 2a and 2b). As expected, truck speeds decreased from a certain value of the grade. However, most of the selected horizontal curves presented a deceleration process that finished between these points, i.e., heavy vehicles adapted their speed before arriving at midpoint (Figure 1). Therefore, heavy vehicle speeds were mainly influenced by the grade at the point of curvature, which was similar to the grade of the preceding tangent.

The trend associated with the grade at the end of the horizontal curve was contrary to the intuition, i.e., the speeds got greater as grade increases (Figures 2c – unloaded trucks). Additionally, using the average grade along the horizontal curve might hide the true influence of the grade (Figure 2d).

So, the grade at the point of curvature was considered in this research.



(a) Grade at the point of curvature (b) Grade at midpoint



(c) Grade at the end (d) Average grade

FIGURE 2 Analysis of the grade.

The number of drivers required for each horizontal curve was also analyzed. For this, the following expression was used:

$$n = \frac{Z^2 \cdot \sigma^2}{e^2} \qquad (2)$$

where n = number of drivers required; Z = quantile of a normal distribution considering a 95% confidence level (1.96); σ = speed deviation (km/h); and e = speed error (2 km/h). As a result, the number of drivers required in most of the selected horizontal curves was lower than 10 drivers mainly due to the low speed deviation observed on these locations. To this regard, the average speed deviation was 1.96 km/h. Even so, the average number of observations was around 80 drivers per horizontal curve.

ANALYSIS

Most of the previous models to predict the operating speed on horizontal curves were calibrated from spot speed data collected at midcurve, assuming the minimum speed was achieved at this location. However, these studies did not verify this hypothesis.

In this research, the minimum speed and the speed at midcurve were obtained from the continuous speed profiles collected. A hypothesis test based on the analysis of paired data was performed to determine whether the operating speed at midcurve (V_{85mc}) could be considered similar to the minimum operating speed (V_{85min}) or not. For each horizontal curve, the following hypotheses were formulated: (a) Null hypothesis H_0: $V_{85mc} - V_{85min} = 0$; (b) Alternative hypothesis H_1: $V_{85mc} - V_{85min} \neq 0$. The confidence level considered in the analysis was 95%.

As a result, the null hypothesis was rejected (*t*=0,82536; *P-Value*=0), i.e., V_{85mc} could not be considered similar V_{85min} at a 95% confidence level. The same test was developed for the 15th percentile speed obtaining the same results.

Therefore, the hypothesis assumed by previous research should not be accepted without a preliminary analysis. In this way, the minimum speed was used for the calibration of speed prediction models.

Operating Speed Model

Descriptive analysis

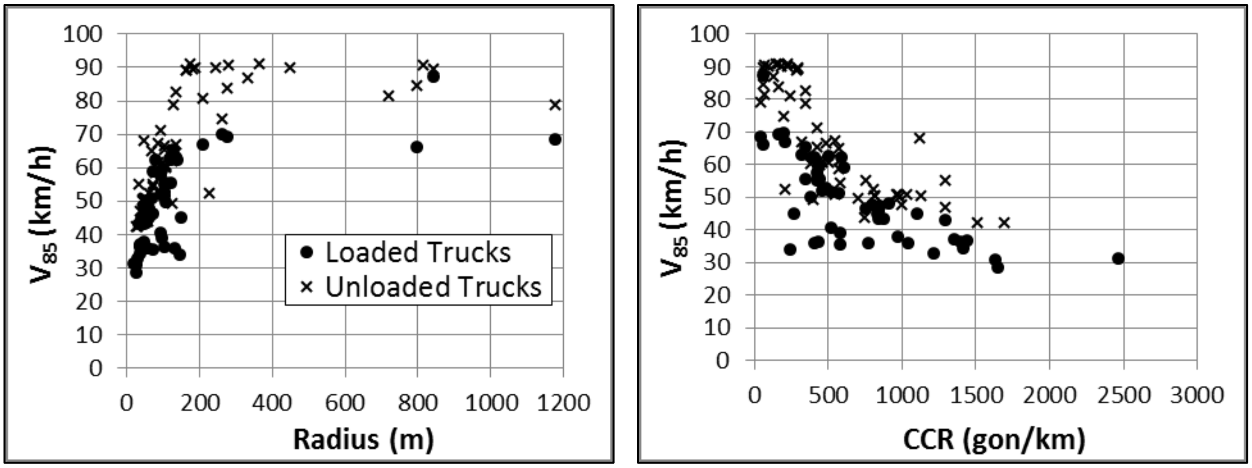
The minimum operating speed (V_{85}) was identified for each horizontal curve from the 85th percentile speed profile.

A preliminary correlation analysis was carried out to identify what horizontal geometric variables presented a greater influence on operating speed. This analysis found that the length of preceding tangent and the length of the curve were weakly correlated with the operating speed. However, the radius of the horizontal curve, the Curvature Change Rate (CCR) and the deflection angle of the horizontal curve presented a great correlation with the operating speed. Specifically, the largest positive correlation coefficient was associated with the radius (0.5650), while the variables with the greatest negative correlation coefficient were associated with the CCR (0.7145) and the deflection angle (0.6058). Figure 3 shows these geometric variables versus the operating speed.

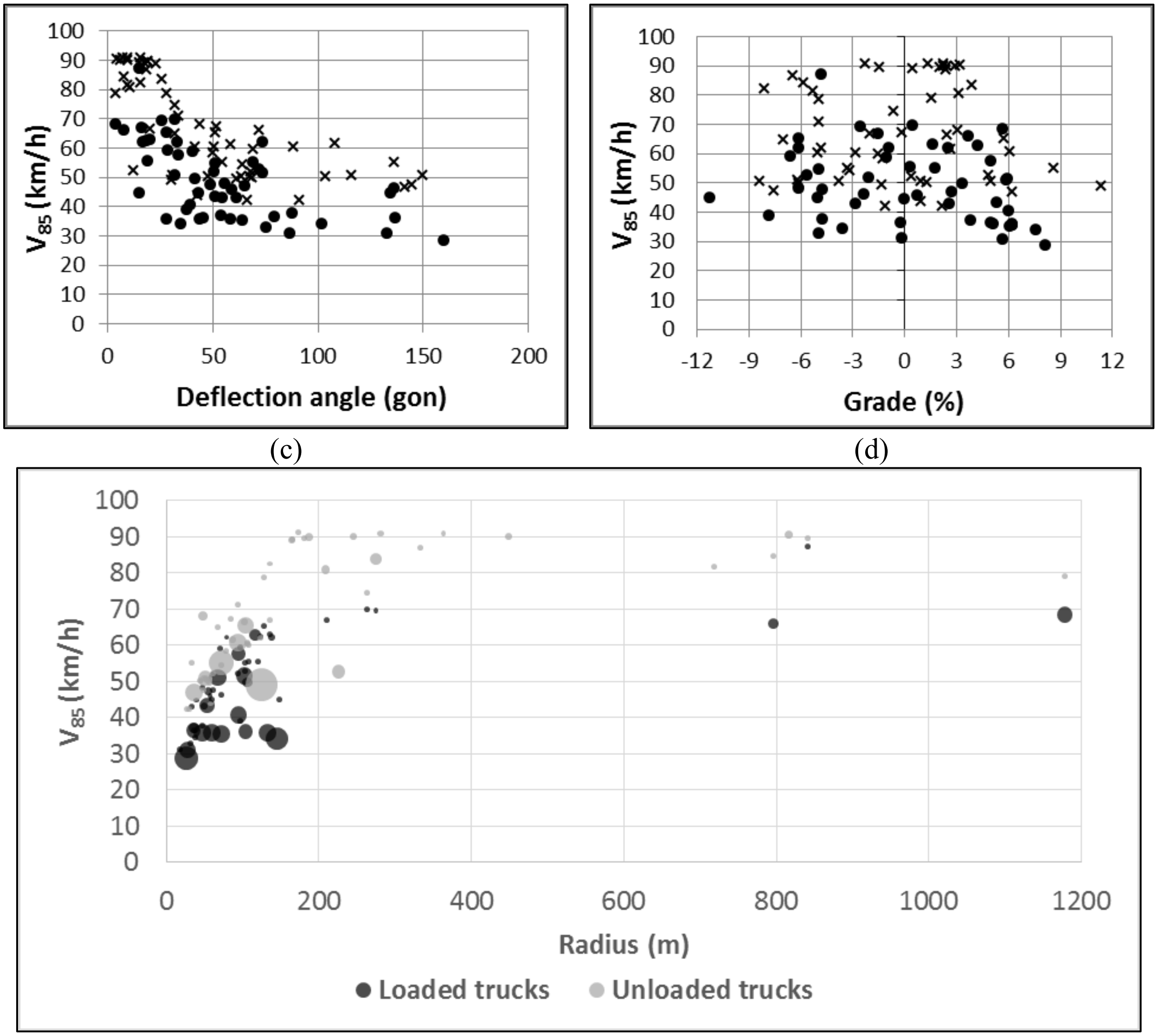
The trend of the data showed clearly two different populations, loaded trucks and unloaded trucks. As expected, the operating speed for loaded trucks was lower than the operating speed for unloaded trucks. So, different regression analyses were performed.

On the other hand, the analysis of the relationship between the vertical alignment and operating speed was focused on the grade. Although the grade was not a significant factor on downgrades, a decreasing trend was observed from a certain value of the grade (Figure 2).

To verify this phenomenon, the relationship between the horizontal and vertical alignment and the operating speed was studied jointly. Figure 3e shows the relationship between the radius, the grade, and the operating speed. Regarding this, the size of each point represents the grade value. It can be observed how operating speed decreased as the grade increased for a given radius.



(a) (b)



(c) (d)

*Point size represents grade values.

(e)

FIGURE 3 Geometric variables vs. Operating speed.

Modeling operating speed

Different regression models were calibrated based on the results obtained above. First, several speed models were developed considering different variables related to the horizontal alignment: radius of the horizontal curve, CCR and deflection angle of the horizontal curve. For this, different functional forms were studied.

This analysis allowed identifying what horizontal geometric variable presented a greater influence on operating speed. The adjusted coefficient of determination was used as goodness of fit. Thus, the most accurate models for loaded and unloaded trucks were based on the radius as the explanatory variable. These models are:

$$V_{85L} = 73.76 - 46.45/e^{0.0072 \cdot R} \qquad R^2_{Adj} = 0.60 \tag{2}$$

$$V_{85U} = 87.55 - 60.37/e^{0.0102 \cdot R} \qquad R^2_{Adj} = 0.74 \tag{3}$$

where V_{85L} = operating speed for loaded trucks (km/h); V_{85U} = operating speed for unloaded trucks (km/h); R = radius of the horizontal curve (m); and R^2_{Adj} = adjusted coefficient of determination.

The vertical alignment was introduced in the previous models to get more accurate speed models. For this, an analysis of the residuals as a function of the grade was carried out. This showed a homogeneous distribution of the residuals around 0 until certain value of the grade, from which a decreasing linear trend was identified. Therefore, a compound model was proposed (Table 3).

It can be observed how the adjusted coefficients of determination increased significantly. This improvement was more obvious for loaded trucks, so these were more influenced by the grade than those unloaded. In this way, the vertical alignment had an important influence on operating speed when the grade was greater than 4.23% for loaded trucks and 3.19% for unloaded trucks. On the contrary, the operating speed only depended on the horizontal alignment when the grade was lower than these values.

TABLE 3 Operating speed models

Operating speed models		
Loaded trucks	$V_{85L} = \begin{cases} 75.96 - \dfrac{44.56}{e^{0.00685 \cdot R}} & if\ g \leq 4.23\% \\ 75.96 - \dfrac{44.56}{e^{0.00685 \cdot R}} - 5.06 \cdot (g - 4.23) & if\ g > 4.23\% \end{cases}$	$R^2_{Adj} = 0.73$
Unloaded trucks	$V_{85U} = \begin{cases} 85.02 - \dfrac{60.62}{e^{0.01240 \cdot R}} & if\ g \leq 3.19\% \\ 85.02 - \dfrac{60.62}{e^{0.01240 \cdot R}} - 1.95 \cdot (g - 3.19) & if\ g > 3.19\% \end{cases}$	$R^2_{Adj} = 0.77$
where V_{85L} = operating speed for loaded trucks (km/h); $V_{85}U$ = operating speed for unloaded trucks (km/h); R = radius of the horizontal curve (m); and g = grade (%); and R^2_{Adj} = adjusted coefficient of determination.		

15th Percentile Speed Model

Descriptive analysis

The calibration of the 15th percentile speed models was based on the minimum 15th percentile speed along each horizontal curve.

The influence of the horizontal and vertical alignment on 15th percentile speed was similar to those observed for the operating speed (Figure 3). In this regard, the most influential variables related to the horizontal alignment were the radius of the horizontal curve, the CCR and the deflection angle, which presented a correlation coefficient with respect to the 15th percentile speed equal to 0.5092, -0.6835 and -0.5734, respectively. Likewise, both loaded and unloaded truck speeds described a declining trend from a certain value of the grade.

Modelling 15th percentile speed

Several regression models were developed to evaluate the horizontal alignment influence on 15th percentile speed. For this, different functional forms were studied and the adjusted coefficient of determination was given in all regressions as goodness of fit.

As a result, Equations 4 and 5 show the most accurate models, which used the radius as the explanatory variable.

$$V_{15L} = 61.00 - 38.93/e^{0.0080 \cdot R} \quad R^2_{Adj} = 0.54 \tag{4}$$

$$V_{15U} = 76.66 - 56.72/e^{0.0108 \cdot R} \quad R^2_{Adj} = 0.69 \tag{5}$$

where V_{15L} = 15th percentile of the distribution of speeds for loaded trucks (km/h); V_{15U} = 15th percentile of the distribution of speeds for unloaded trucks (km/h); R = radius of the horizontal curve (m); and *R squared* = coefficient of determination.

In addition, some speed models were calibrated considering both horizontal and vertical alignment. For this, the residuals of the previous models were analyzed as a function of the grade. To this regard, a decreasing linear trend was identified from a certain value of the grade. Therefore, the same functional form used for the operating speed was proposed (Table 4).

As a result, the grade showed an important influence on speed from 3.14% and 3.06% for loaded and unloaded trucks, respectively. As expected, introducing the vertical alignment in the models improved their accuracy, since the adjusted coefficient of determination increased significantly.

TABLE 4 15th percentile speed models

15th percentil speed models		
Loaded trucks	$V_{15L} = \begin{cases} 64.17 - \dfrac{37.24}{e^{0.00720 \cdot R}} & if\ g \leq 3.14\% \\ 64.17 - \dfrac{37.24}{e^{0.00720 \cdot R}} - 3.28 \cdot (g - 3.14) & if\ g > 3.14\% \end{cases}$	$R^2_{Adj} = 0.69$
Unloaded trucks	$V_{15U} = \begin{cases} 76.74 - \dfrac{57.58}{e^{0.01185 \cdot R}} & if\ g \leq 3.06\% \\ 76.74 - \dfrac{57.58}{e^{0.01185 \cdot R}} - 2.43 \cdot (g - 3.06) & if\ g > 3.06\% \end{cases}$	$R^2_{Adj} = 0.74$
where V_{85L} = operating speed for loaded trucks (km/h); V_{85}U = operating speed for unloaded trucks (km/h); R = radius of the horizontal curve (m); and g = grade (%); and R^2_{Adj} = adjusted coefficient of determination.		

DISCUSSION

Most of the studies about the heavy vehicle speeds presented a deficient data collection due to the number of locations, the number of observations, and the data collection methodology. To this regard, this research has been developed from continuous speed profiles collected along a large number of horizontal curves.

The continuous speed profiles allowed analyzing the hypothesis that there is not significantly difference between the speed at midcurve and the minimum speed along the horizontal curve. As a result, this hypothesis was rejected and, consequently, the minimum speed was statistically lower than the speed at midcurve at a 95% confidence level.

The most influential variable on truck speeds was the radius. This result was consistent with the outcomes obtained in previous research *(2, 6, 17)*. Regarding this, the influence of the radius on heavy vehicle speeds was different depending on whether the vehicle was loaded or not. For unloaded trucks, the radius was dominant up to values around 200 m. This means that for radius lower than 200 m, a low radius variation leads to a great speed variation. Conversely, a great radius variation was needed to observe a significant speed variation when the radius was greater than 200 m. However, the influence of the radius was greater for loaded trucks, since a high influence was identified up to a radius of 300 m. This is due to the loaded trucks present a greater height of gravity center.

Despite identifying the same trend according to the radius of the horizontal curve, the new operating speed models estimated greater speeds than the model developed by Jacob and Anjaneyulu *(7)*. This phenomenon was likely due to the difference between the Spanish and Indian two-lane rural roads, which present different posted speed limits and type of heavy vehicles. Regarding this, the trucks considered in this research might have a lower weight-to-power ratio (WPR) than the heavy vehicles considered by Jacob and Anjaneyulu (Figure 4).

It should be noted that loaded trucks had higher predicted speeds than unloaded trucks for the very low radius ($R < 20$ m). Thus, these models should be used for radius greater than 20 m.

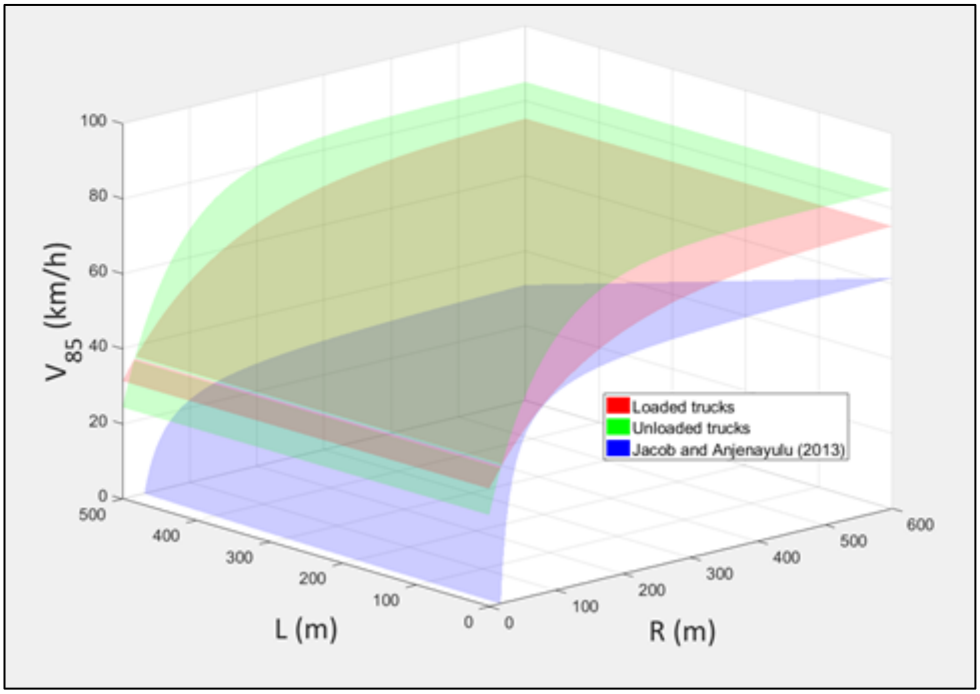


FIGURE 4 Operating speed models vs. Jacob and Anjaneyulu's model.

On the other hand, the grade at the point of curvature also presented a great influence on truck speeds. Contrary to expectations, the grade threshold was lower for unloaded trucks (3%) than for loaded ones (4%) according to the 85th percentile speed models. Regarding the 15th percentile speed models, heavy vehicle speeds decreased for grades greater than 3% for both loaded and unloaded trucks. However, the influence of the grade was higher for loaded trucks than for unloaded trucks, since the regression coefficients related to loaded trucks were greater.

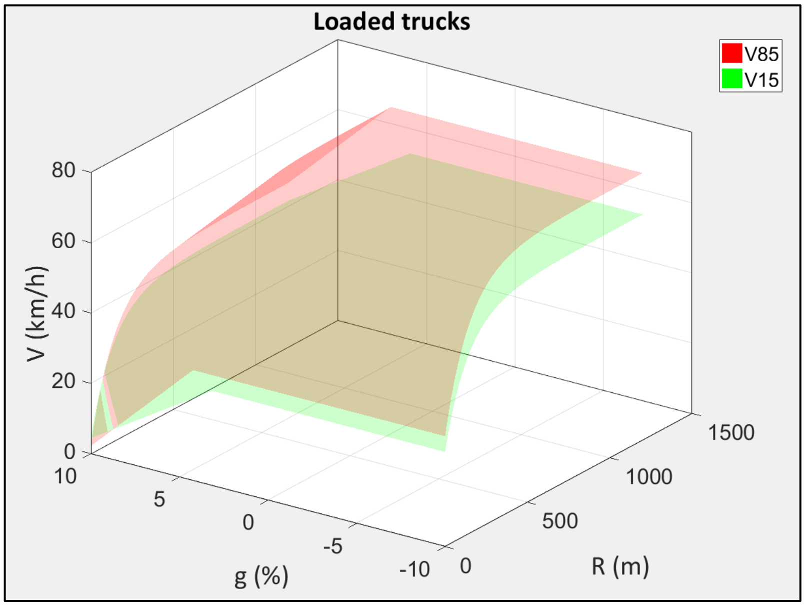
Other authors pointed out that the heavy vehicle speeds decreased as the grade increased, but not from a certain grade value *(2, 17)*. Surely, these conclusions were related to the geometric characteristics of the horizontal curves under study. Specifically, Morris and Donnell studied the truck speeds on multilane highways, which usually present greater radius and tangent lengths *(17)*. In this situation, drivers are not as influenced by the horizontal alignment as on two-lane rural roads, where this alignment predominates over the vertical alignment on downgrades.

According to Donnell et al *(2)*, the operating speed at midcurve was also influenced by the length and grade of the departure tangent. Related to this, this study concluded that the grade at the point of curvature significantly influenced on truck speeds, which was similar to the grade of the preceding tangent for most of the horizontal curves. So, geometric and operating characteristics of the approach tangent have an important effect on horizontal curve speed, what requires further research.

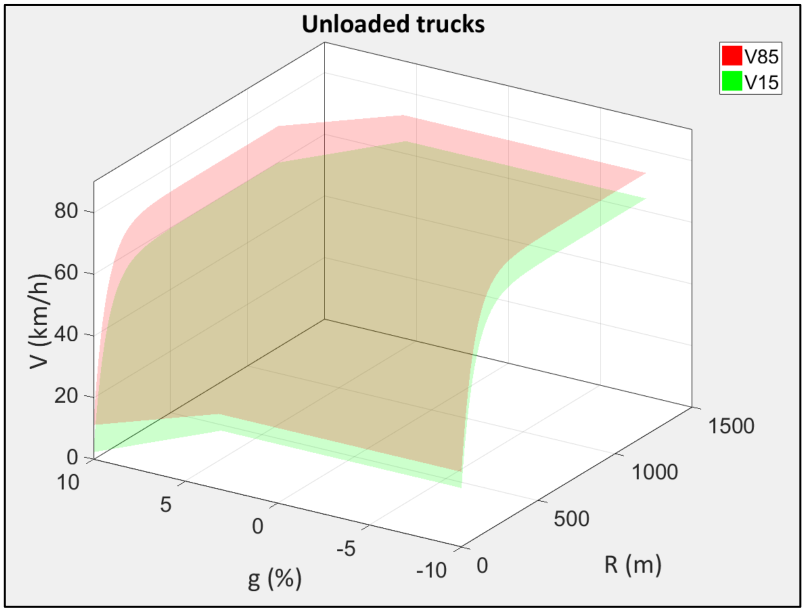
Finally, a comparison between 85th and 15th percentile speed models was carried out (Figure 5). The difference between both speed percentiles got lower as the radius decreased for both loaded and unloaded trucks, i.e., sharper geometries produced lower speed deviations. In addition, the difference between both speed percentiles was lower for unloaded trucks than for loaded ones. As an example, this speed difference was approximately 8 km/h for unloaded trucks considering high values of the radius, whereas this speed difference increased to 12 km/h for loaded trucks. Therefore, loaded trucks underwent a greater speed deviation than unloaded ones discounting the effects of the vertical alignment.

Regarding vertical alignment, a different trend was observed depending on whether the vehicle was loaded or not. For loaded trucks, the difference between both speed percentiles was lower as the grade increased. On the contrary, the speed difference got greater as the grade increased for unloaded trucks. In this way, loaded trucks presented a lower speed deviation than unloaded trucks just focusing on the vertical alignment.

Thus, loaded trucks were more influenced by the vertical alignment and unloaded trucks were more influenced by the horizontal alignment.



(a)



(b)

FIGURE 5 Comparison between 85th and 15th percentile speed models

CONCLUSIONS AND FURTHER RESEARCH

The development of truck speed profiles is fundamental to evaluate the interaction between passenger cars and heavy vehicles, which is a critical factor on road safety. However, this phenomenon is rarely considered due to the lack of truck speed models.

This study presents several speed models, which include geometric characteristics as explanatory variables to predict truck speeds on horizontal curves of two-lane rural roads. These models were calibrated based on the minimum speed identified from continuous speed profiles collected using Global Positioning System (GPS) tracking devices.

The results showed the combined effect of the horizontal and vertical alignment on truck speeds. To this regard, the most influential variables were the radius of the horizontal curve and the grade at the point of curvature. In addition, two different trends were identified which were related to loaded and unloaded trucks.

The influence of the vertical alignment was only observed on upgrades. In this way, operating speed decreased for grade values greater than 4% and 3% for loaded and unloaded trucks, respectively. In addition, the influence of the grade was greater for loaded trucks than for unloaded trucks.

85th and 15th percentile speed models were calibrated for both loaded and unloaded trucks. These models were compared with those developed previously. Although the same trends were observed, the use of the proposed models are only recommended on Spanish two-lane rural roads due to the different characteristics of heavy vehicles among countries.

The models presented in this research are part of the development of a new operating speed profile for heavy vehicles. The continuous speed profiles collected in this research will be used to develop speed models on tangents and analyze tangent-to-curve speed variations, and acceleration and deceleration rates. This will allow completing the truck operating speed profile model. In this way, the interaction between passenger cars and heavy vehicles will be able to be considered in the analysis of the geometric design consistency.

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