OPERATING SPEED MODELS FOR HEAVY VEHICLES ON TANGENTS OF SPANISH TWO-LANE RURAL ROADS

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ABSTRACT

Road safety is one of the most important public health concern in our society. In Spain, the most of the traffic accidents involving a heavy vehicle occur on two-lane rural roads. Current consistency models only rely on the analysis of the operating speed profile for passenger cars due to the few speed models available for heavy vehicles.

Therefore, the main objective of this research was to analyze and model the free flow speed developed by heavy vehicles on tangents of two-lane rural roads.

Thus, this research presents new speed models for estimating heavy vehicle speeds on tangents of two-lane rural roads. To do this, truck speeds were collected by means of Global Positioning System tracking devices, on 49 tangents sections that were identified from 12 road sections.

Two different patterns were detected, which were associated with loaded and unloaded trucks. The combined effect of geometric and operational variables was analyzed. As a result, the most influential variables on loaded truck speeds were the speed of the preceding horizontal curve and the grade of the tangent, whereas unloaded truck speeds were significantly influenced by the length of the tangent and the speed of the preceding horizontal curve.

Finally, several regression models were calibrated to predict the 85th and 15th percentile speeds for both loaded and unloaded trucks.

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

INTRODUCTION

Road safety is one of the most important public health concern in our society. Indeed, around 1.2 million people die and 50 million are injured in road crashes every year *(1)*. In this regard, the main concurrent factors on road safety are the driver, the vehicle, and the infrastructure.

Geometric design consistency, which can be defined as how drivers' expectancies and road behavior relate, aims to assess road safety in both new and existing highways. A consistent road allows road users a harmonious driving experience free of surprises, whereas an inconsistent road might lead to important unexpected events to drivers, producing an anomalous behavior and rising the likelihood of crash occurrence.

The most commonly used method to assess geometric design consistency relies on the study of the operating speed profile. This speed is usually defined as the 85th percentile of the speed distribution under free-flow conditions with no environmental restrictions (V_{85}), which can be predicted by using operating speed models.

Although there are a lot of models that allow highway engineers to obtain the operating speed for passenger cars on two-lane rural roads, the existing models for heavy vehicles are very few. Thus, most current consistency models do not consider the operating speed profile of heavy vehicles.

However, not considering heavy vehicle speeds in road safety analysis might lead to inconsistent road designs because the interaction between both passenger cars and heavy vehicles is a key factor in road crash occurrence, mainly on two-lane rural roads with a high percentage of heavy vehicles *(2)*.

Some researchers have assessed this phenomenon by analyzing the speed difference between heavy vehicles and passenger cars. Regarding this, Harwood et al. *(3)* pointed out that this speed difference might mainly produce inconsistencies on vehicle operation on upgrades, whereas Leisch and Leisch *(4)* concluded that this speed difference should not be larger than 15 km/h.

Unlike passenger cars, heavy vehicles are characterized by more complex systems with a variety of possible failure modes and performance features including locked-wheel braking, trailer swing-out, rollover, poor acceleration characteristics, and longer braking distance. In addition, heavy vehicle weight is closely related to fatal crash rate *(5)*.

On the other hand, the American Association of State Highway and Transportation Officials (AASHTO) identified that crash risk increases as vehicle speed largely deviates from the road mean speed *(6)*. Additionally, a positive correlation between crash rates and speed reduction was observed on upgrades. In this regard, the speed reduction of heavy vehicles depended on the grade of the road and the characteristics of the vehicle, so a different operational behavior exists between heavy vehicles and passenger cars *(7)*. These conclusions were used by the AASHTO *(6)* to design climbing lanes and by Polus et al. *(8)* to assess geometric design consistency.

Most previous models were focused on the speed prediction on horizontal curves because the speed estimation on tangents was found to be more complex and led to opposite findings *(9)*. Lamm et al. *(10)* classified tangents as independent and non-independent tangents based on whether the length of the tangent allowed drivers to reach the desired speed or not. For non-independent tangents, drivers' speed was influenced by the length of the tangent and the degree of curvature and the deflection angle of the preceding horizontal curve. The influence of the adjacent horizontal curves was greater as the length of the tangent decreased. Thus, the variable with the greatest influence on independent tangents was the length of the tangent, but it was not statistically significant *(11)*.

Ottesen and Krammes *(12)* also identified that the most significant variable was tangent length. Moreover, this study revealed that other environmental variables, such as the type of region and the type of terrain, had a significant effect on long tangents.

On the contrary, Polus et al. *(13)* concluded that the speed along short tangents (<150 m) was not influenced by the length of the tangent. However, heavy vehicle speeds on long tangents (>1,000 m) with reasonable adjacent radii (>250 m) were significantly influenced by tangent length.

On the other hand, Boroujerdian et al. *(14)* studied the effect of road grade and its interaction with other geometric and operational parameters on the speed along 42 two-lane rural road sections in Iran. The results showed that the speed at the beginning of the tangent, the interaction between vehicle type (passenger car or heavy vehicle), and road grade were the most significant parameters. This means that the characteristics of the previous section has an important effect on vehicle speeds.

There are other prediction speed models for heavy vehicle speeds based on cinematic and dynamic performance, which are commonly used for the analysis of ascending lanes (15-18). These models rely on the vehicle weight-to-power ratio (WPR), the grade, pavement characteristics, the resistance of the air, the coefficient of friction, and rolling resistance coefficients. It should be noted that some of these models are included in the geometric design guidelines of the United States *(6),* Spain *(19),* Colombia *(20),* and Chile *(21)*, among other countries.

These models assume that the speed at the beginning of the upgrade decreases towards a minimum speed, which remains constant until the end of the section. However, the speed variation along short upgrades (L < 1000 m) is different. In this case, heavy vehicles are able to accelerate during the last third of the section due to the remaining tractive force *(22)*.

Finally, Saifizul et al. *(23)* studied the influence of the vehicle weight and size on heavy vehicle speeds. As a result, a great speed difference was identified when the size of the vehicles was different. On the contrary, when vehicles were very similar in size but had different number of axles, the most influential factor was the gross vehicle weight.

Others authors used a system modeling approach to predict passenger car and truck operating speeds on multilane highways with combinations of horizontal curves and steep vertical grades. Mean operating speeds were modeled as a function of several geometric design features and the traffic control devices present at each study site. Further, the possible endogenous relationship between passenger car and truck speeds was investigated. The findings indicate that vertical grades appear to have a more significant influence on truck operating speeds than on passenger car speeds. Increasing the lane width, however, was associated with higher truck operating speeds; the right shoulder width was not associated with truck operating speeds. Higher posted speed limits were associated with higher truck and passenger car operating speeds *(24)*.

In conclusion, few heavy vehicle speed models are available, especially models for estimating heavy vehicle speeds on tangents. Besides, most of these studies used spot speed data collected on a low number of tangents and presented a large variation in model form, explanatory variables, and regression coefficients.

This might lie in differences in mechanical characteristics of the vehicles, driver behavior, and road geometry among countries.

Therefore, this research studies heavy vehicle speeds on tangent sections of two-lane rural highways. For this purpose, continuous speed profiles were collected through Global Positioning System tracking devices on 12 road sections.

Summarizing, few operating speed models for heavy vehicles have been calibrated.

OBJECTIVE AND HYPOTHESES

This study aims at developing a new prediction speed model to estimate heavy vehicle speeds on tangents of two-lane rural roads. To do this, the influence of different geometric and operational variables on truck speeds was analyzed.

Although most previous studies are only focused on the calibration of the 85th percentile speed, this research also propose the analysis of the 15th percentile speed, because the lower percentiles are prone to produce traffic conflicts between heavy vehicles and passenger cars such as rear-end crashes.

The first hypothesis of the study is related to the grade of the road. Although the grade influences on passenger cars speeds only when it is high ($g > 6$ %), heavy vehicles are expected to experience important speed reductions on upgrades. On the other hand, the speed deviation between heavy vehicles with similar weight is expected to be very low because, although passenger car speeds mainly depend on drivers' behavior, heavy vehicle speeds are significantly affected by the vehicle mechanical features, such as the weight-to-power ratio (WPR).

METHODOLOGY

This study is part of a wider research that aims at developing a new operating speed profile for heavy vehicles. Thus, the methodology of this research is similar to that explained in Llopis-Castelló et al. *(25)*, which shows the development of heavy vehicle speed models on horizontal curves. Speed data collection was developed through three transport companies, which equipped their heavy vehicles with small-size 1 Hz Global Positioning System (GPS) tracking devices that, thanks to the powerful magnet they possess, was placed on the outside of the vehicle cab. In this way, the continuous speed profile of every vehicle was obtained. The geometry of the road sections was obtained following the procedure developed by Camacho-Torregrosa et al. *(26)*. Finally, the relationship between truck speeds on tangents and different geometric and operational variables was analyzed and different regressions models were calibrated to predict heavy vehicle speeds on tangents.

DATA COLLECTION

A total of 83 drivers with their own heavy vehicle took part of the data collection. All vehicles are 5 axles, single trailer trucks, with a weight-to-power ratio (WPR) ranged from 35 to 54 kg/kW for unloaded trucks, being its average value 43 kg/kW. For loaded trucks the WPR varied from 112 to 131 kg/kW, being its average value 120 kg/kW. In this case, the WPR was calculated with the gross-weight. As mentioned, these vehicles were equipped with 1Hz pocket-sized GPS tracking devices. Then, these carried out round trips, loaded in one direction and unloaded in the other direction, along 12 road sections of two-lane rural roads, which take part of the usual routes of these vehicles, on working days under favorable weather conditions.

These road sections are located in the Region of Valencia (Spain) (Table 1), without major intersections, good pavement conditions and rural environment. The lane width varied between 3.0 and 3.5 m, while the paved shoulder width ranged between 1.0 and 1.5 m. The horizontal alignment of the studied road sections was obtained by means of an algorithm based on the heading direction (*26*), whereas the vertical alignment was recreated through the geometric road design software Autodesk Civil 3D. In this case, the speed limit (90 km/h) is the same for all 12 road sections and for all types of heavy vehicles.

TABLE 1 Road sections

Road	Name of the Section	Length (m)	Grade (%)	
			Minimum	Maximum
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	CV-580 - La Matrona I	1,062	-1	+8
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

Collected data was filtered and processed following the methodology described in Llopis-Castelló et al. *(25)*. First, the individual speed profile of each vehicle was obtained, and the free-flow conditions were checked *(27)*. This test relies on the hypothesis of every single driver behaves according to a specific speed percentile. This is based on the hypothesis that every single driver behaves in a particular way, i.e., in a particular percentile of the speed distribution. Therefore, a sudden change in its usual operating percentile is associated with a non-free-flow conditions, since his/her behavior has been significantly modified. After removing non-free-flow sections for all drivers, the 85th and 15th percentile speed profiles were calculated.

The selection of tangents was carried out by means of the analysis of the speed profiles of the 12 road sections (Figure 1). Only tangents which has a constant grade and allowed drivers to reach their desired speed were selected. It is defined as the speed that the driver wants to maintain when the geometry and other variables (such as visibility) do not restrict him. It is associated with reaching a constant speed along the length of the tangent. This situation does not only depend on the length of the tangent but also on the characteristics of the preceding horizontal curve. Thus, the maximum speed outside the acceleration and deceleration zones were identified for each tangent.

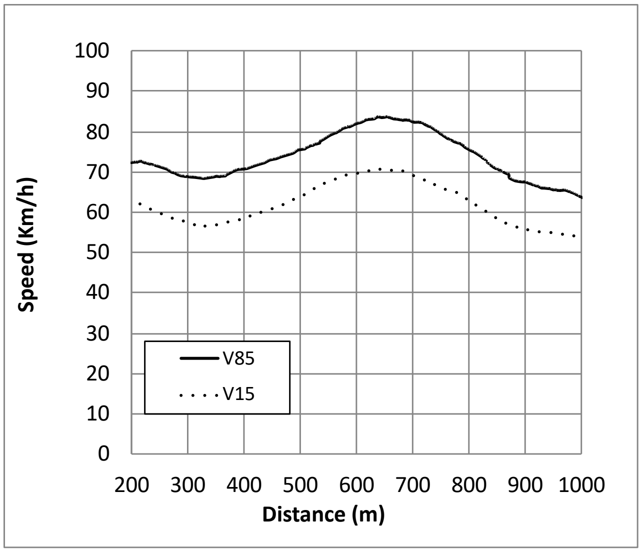
As a result, 59 tangents with constant longitudinal grade were considered in this research, which were travelled by a minimum of 14 vehicles and a maximum of 135 vehicles, with an average of 90 heavy vehicles per tangent. Table 2 shows the most important geometric features of the studied tangents.

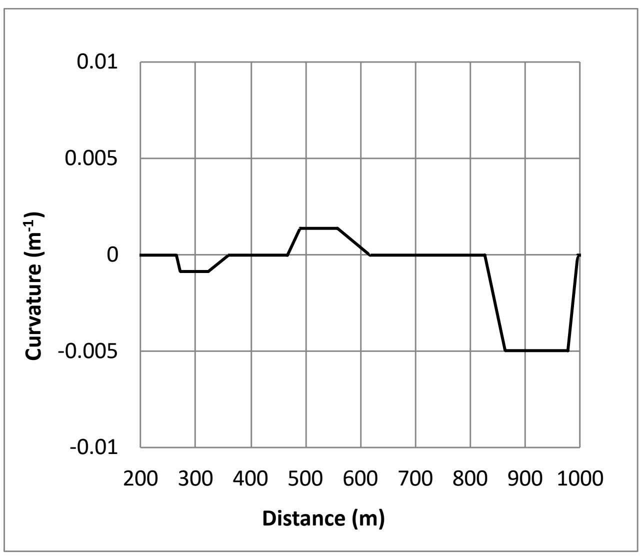
TABLE 2 Statistical summary of geometric variables at tangents

Variable	Notation	Minimum	Maximum	Mean	Standard deviation
Tangent length (m)	L	30.00	1,359.00	163.13	299.39
Grade (%)	g	-10.64	10.64	0.44	5.45
Radius of preceding horizontal curve (m)	R_{C1}	26.00	796.00	89.81	135.00
Radius of successive horizontal curve (m)	R_{C2}	26.00	458.00	81.54	91.80
Curvature Change Rate (gon/km)	CCR	65.6	1,152.71	341.94	211.6

$$CCR = \frac{|\Sigma\gamma|}{L}$$

where *CCR* = curvature change rate of the homogeneous road segment (gon/km); γ = deflection angle of the road segment (gon); and L = length of the road section (km).





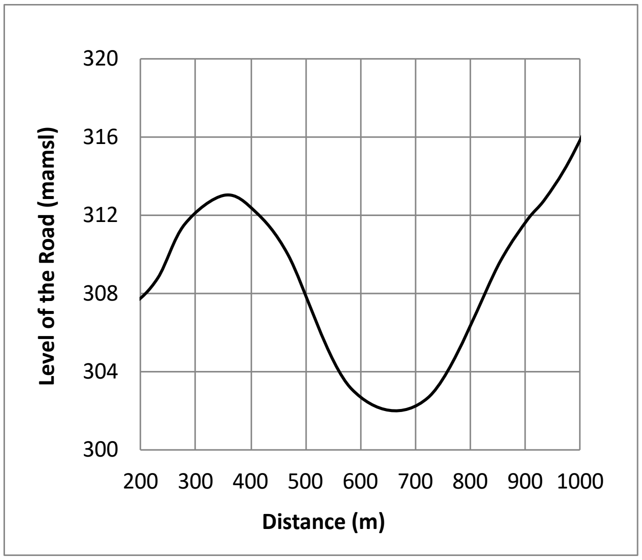


FIGURE 1 Tangent selection.

Finally, the 12 road sections were divided into homogenous road segments considering the traffic volume, cross-section features, presence of major intersections, and geometric behavior. Firstly, road sections were split into segments with similar traffic volume and cross-section. After that, major intersections were identified and considered for segmentation, since they can significantly influence drivers' behavior. Finally, the road sections were divided regarding its geometric behavior using the German methodology, which is based on the analysis of the geometric parameter Curvature Change Rate (*CCR*). This parameter is the ratio between the sum of the absolute deflection angles and the length of the road segment, which must be plotted in a graphic (Figure 2). In this way, homogeneous road segments are associated to similar *CCR* behavior, i.e., similar slope in the chart.

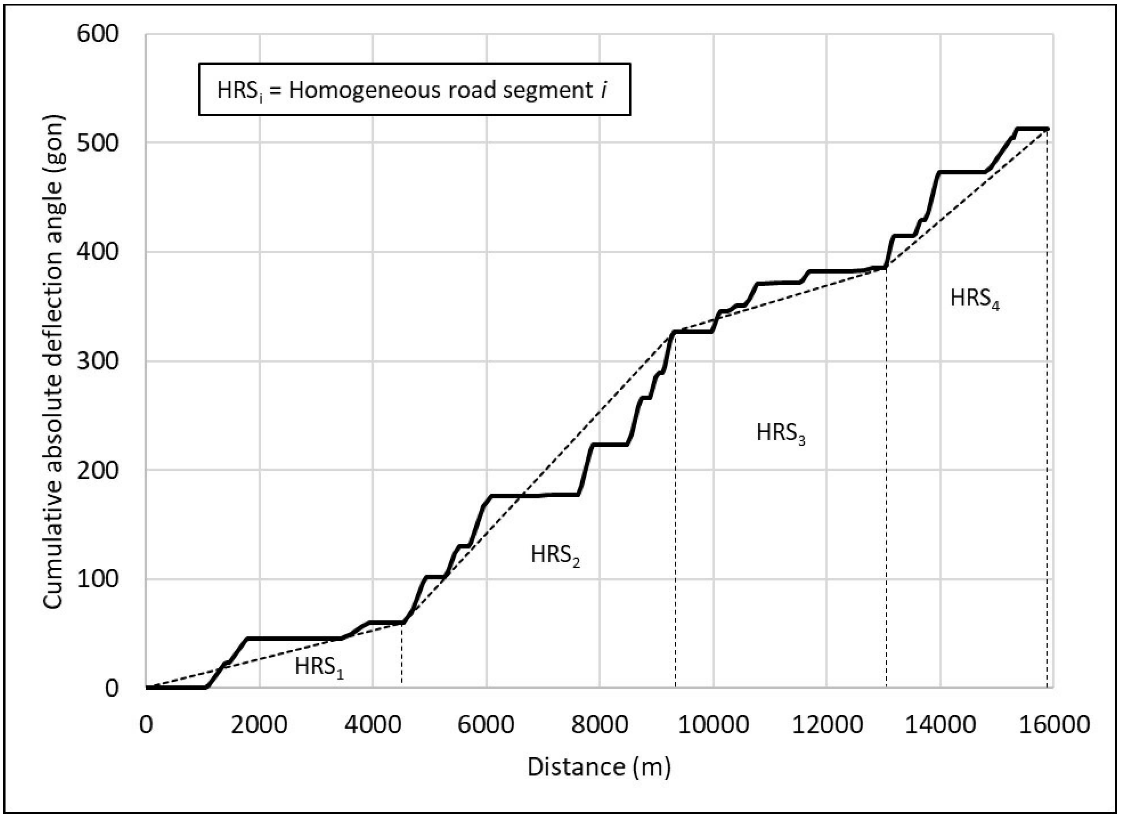


FIGURE 2 Identification of homogeneous road segments.

ANALYSIS

The analysis aimed at identifying which geometric and operational variables have a greater influence on truck speeds. The considered geometric variables were the tangent length (L), the grade (g), the radius of the preceding horizontal curve (R_{C1}), the radius of the successive horizontal curve (R_{C2}), the length of the preceding horizontal curve (L_{C1}), the length of the successive horizontal curve (L_{C2}), the deflection angle of the preceding horizontal curve (γ_{C1}), the deflection angle of the successive horizontal curve (γ_{C2}), the Curvature Change Rate of the homogeneous road segment (CCR), the Curvature Change Rate of the tangent and its adjacent horizontal curves ($CCR_{C\_T\_C}$), the Curvature Change Rate of the preceding horizontal curve and tangent (CCR_{C_T}), and the Curvature Change Rate of the preceding horizontal curve (CCR_C). The studied operational variable was the minimum 85th percentile speed of the preceding horizontal curve (V_{pc}).

Number of vehicles

The number of vehicles required for each tangent was previously studied. Thus, the Equation 1 was used:

$$n = \frac{Z^2 \cdot \sigma^2}{e^2} \quad (1)$$

where n = the number of vehicles required; Z = the quantile of a normal distribution considering a 95% confidence level (1.96); σ = the speed deviation (km/h); and e = the assumed speed error (2 km/h).

In this way, the number of vehicles required in most of the studied tangents was lower than 20 vehicles due mainly to the low speed deviation experienced on these locations, which ranged from 0.14 to 14.2 km/h with an average value equal to 1.65 km/h. Even so, the average number of vehicles was 90 trucks per tangent ranging from 14 to 135 in the selected tangents.

85th Percentile Speed Model

Descriptive analysis

The maximum operating speed (V_{85}) was obtained for each tangent from the 85th percentile speed profiles.

A preliminary correlation analysis was performed to determine which geometric and operational variables have a larger influence on 85th percentile speed. However, two clearly different patterns were found, which were associated to loaded and unloaded trucks. Thus, this correlation analysis was carried out for loaded and unloaded trucks separately (Table 3).

TABLE 3 Correlation analysis of the 85th percentile speed

(a) Loaded trucks

VARIABLES		V_{85}	L	V_{85pc}	R_{C1}	L_{C1}	γ_{C1}	R_{C2}	L_{C2}	γ_{C2}	$CCR_{C\_T\_C}$	CCR_{C_T}	CCR_C	CCR
V_{85}	R	1												
	Valor P													
L	R	0.79797	1											
	Valor P	2.67E-08												
V_{85pc}	R	0.93587	0.75979	1										
	Valor P	0	2.93E-07											
R_{C1}	R	0.36497	0.42706	0.40381	1									
	Valor P	0.03676	0.01319	0.01978										
L_{C1}	R	0.23161	0.25891	0.21869	0.11319	1								
	Valor P	0.19467	0.1457	0.22145	0.53054									
γ_{C1}	R	-0.34352	-0.30283	-0.3491	-0.48581	0.59974	1							
	Valor P	0.05031	0.0867	0.04646	0.00416	0.00023								
R_{C2}	R	0.30502	0.21516	0.33563	0.08456	0.08198	-0.12608	1						
	Valor P	0.08434	0.22918	0.05619	0.63988	0.65017	0.48445							
L_{C2}	R	0.28419	0.24443	0.24513	0.16205	0.48049	0.22034	-0.02653	1					
	Valor P	0.10896	0.17041	0.16914	0.36759	0.00465	0.21789	0.88347						
γ_{C2}	R	-0.18408	-0.09854	-0.27236	0.0885	0.04026	0.07335	-0.58694	0.51591	1				
	Valor P	0.30513	0.58536	0.12517	0.62431	0.82394	0.68497	0.00033	0.00212					
$CCR_{C\_T\_C}$	R	-0.77411	-0.6365	-0.71355	-0.38114	-0.17199	0.47303	-0.45562	-0.16094	0.39016	1			
	Valor P	1.26E-07	0.00007	3.14E-06	0.02864	0.33854	0.00543	0.00771	0.37092	0.02479				
CCR_{C_T}	R	-0.63966	-0.52051	-0.56788	-0.53049	0.10468	0.75757	-0.17501	-0.11225	0.04509	0.83463	1		
	Valor P	0.00006	0.0019	0.00057	0.00149	0.5621	3.32E-07	0.32999	0.53399	0.80321	1.57E-09			
CCR_C	R	-0.60991	-0.48451	-0.62251	-0.74844	-0.27542	0.50567	-0.3092	-0.18961	0.17117	0.76336	0.74225	1	
	Valor P	0.00016	0.00427	0.00011	5.49E-07	0.12082	0.00268	0.07995	0.29057	0.34087	2.39E-07	7.64E-07		
CCR	R	-0.63031	-0.49392	-0.61146	-0.22411	-0.40607	-0.02182	-0.28892	-0.27462	0.25665	0.66066	0.37063	0.49701	1
	Valor P	0.00008	0.00349	0.00016	0.20992	0.01904	0.90404	0.10295	0.12195	0.14936	0.00003	0.03373	0.00326	

(b) Unloaded trucks

VARIABLES		V_{85}	L	V_{85pc}	R_{C1}	L_{C1}	γ_{C1}	R_{C2}	L_{C2}	γ_{C2}	$CCR_{C\_T\_C}$	CCR_{C_T}	CCR_C	CCR
V_{85}	R	1												
	Valor P													
L	R	0.78237	1											
	Valor P	2.81E-06												
V_{85pc}	R	0.76943	0.37588	1										
	Valor P	6.94E-06	0.06406											
R_{C1}	R	0.38691	0.19571	0.51412	1									
	Valor P	0.05604	0.34846	0.00856										
L_{C1}	R	0.40302	0.23119	0.2431	0.04516	1								
	Valor P	0.04576	0.26617	0.24162	0.83027									
γ_{C1}	R	-0.25028	-0.02916	-0.47442	-0.63512	0.45521	1							
	Valor P	0.22756	0.88996	0.01657	0.00065	0.02223								
R_{C2}	R	0.74456	0.68099	0.41642	0.07384	0.08	-0.19771	1						
	Valor P	0.00002	0.00018	0.03839	0.72577	0.70385	0.34346							
L_{C2}	R	0.20443	0.16592	0.10665	-0.08533	0.40254	0.16412	0.21428	1					
	Valor P	0.32697	0.428	0.61189	0.68507	0.04605	0.43307	0.3037						
γ_{C2}	R	-0.4163	-0.38722	-0.21366	-0.2306	0.2025	0.2345	-0.53377	0.61139	1				
	Valor P	0.03846	0.05583	0.30511	0.26742	0.33166	0.2592	0.00599	0.00117					
$CCR_{C\_T\_C}$	R	-0.83113	-0.62981	-0.51967	-0.44349	-0.13392	0.38406	-0.68449	0.0773	0.70209	1			
	Valor P	2.67E-07	0.00074	0.00776	0.02638	0.52333	0.05804	0.00016	0.71343	0.00009				
CCR_{C_T}	R	-0.7521	-0.53167	-0.51813	-0.59237	-0.06649	0.58351	-0.53368	-0.04698	0.44813	0.90104	1		
	Valor P	0.00001	0.00623	0.00797	0.00181	0.75219	0.0022	0.006	0.82353	0.02467	8.20E-10			

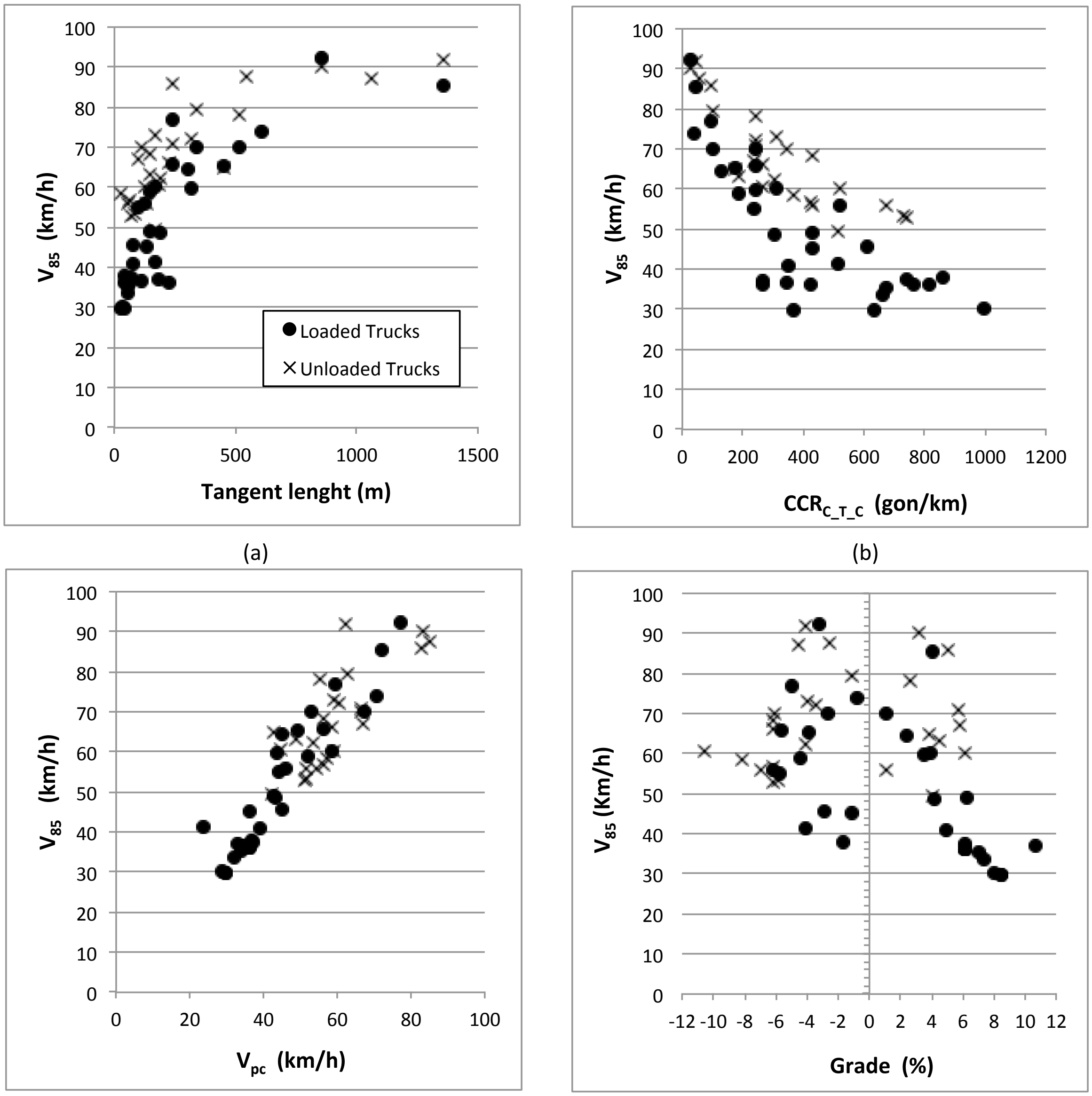
CCR_C	R	-0.57192	-0.18233	-0.65311	-0.663	-0.28332	0.65462	-0.30439	-0.16728	0.1062	0.50705	0.68096	1	
	Valor P	0.00282	0.38304	0.0004	0.0003	0.16994	0.00038	0.13904	0.42415	0.61338	0.00968	0.00018		
CCR	R	-0.67754	-0.50633	-0.52043	-0.29195	-0.27548	0.15975	-0.50854	-0.24627	0.24997	0.61082	0.53681	0.34512	1
	Valor P	0.0002	0.0098	0.00765	0.15675	0.18259	0.44559	0.00944	0.23535	0.22816	0.00118	0.00566	0.0911	

Regarding the horizontal alignment influence, the variables that resulted in the largest correlation coefficients were tangent length (L) and the Curvature Change Rate of the tangent and its adjacent horizontal curves ($CCR_{C\_T\_C}$). Specifically, the correlation coefficients associated with tangent length were 0.7980 for loaded trucks and 0.7824 for unloaded trucks (Figure 3a), whereas the correlation coefficients related to $CCR_{C\_T\_C}$ were -0.7741 and -0.8311 for loaded and unloaded trucks, respectively (Figure 3b).

Furthermore, the influence of the vertical alignment on 85th percentile speed was based on the grade (g). Although the grade did not show a significant influence on downgrades, a declining trend was identified from a specific value of the grade on upgrades (Figure 3d). However, this trend only was observed for loaded trucks. This might be explained through the maximum value of the grade under both conditions. While the maximum grade was 12% for loaded truck speeds, this value was equal to 6% for unloaded truck speeds

Finally, it is worth noting that the 85th percentile speed of the preceding horizontal curve (V_{pc}) also showed an important influence on truck speeds (Figure 3c). Specifically, the correlation coefficients associated with this variable were 0.9359 and 0.7694 for loaded and unloaded trucks, respectively.

As expected, the 85th percentile speed for unloaded trucks was larger than the 85th percentile speed for loaded trucks. In this way, different regression models were developed.



(c) (d)

FIGURE 3 Geometric and operational variables vs. 85th percentile speed.

Modeling 85th percentile speed

Several speed models were calibrated considering the following geometric variables based on the horizontal alignment: tangent length (L) and the Curvature Change Rate of the tangent and its adjacent horizontal curves ($CCR_{C\_T\_C}$).

To do this, the functional forms proposed in Table 4 were analyzed, which try to model the asymptotic trend observed in the descriptive analysis. The adjusted coefficient of determination (R^2_{adj}) was given for each model as a measure of goodness of fit.

TABLE 4 Functional form studied

Functional form
$\boldsymbol{V = \beta_1 + \beta_2 / X}$
$\boldsymbol{V = \beta_1 + \beta_2 / (X + \beta_3)}$

$\boldsymbol{V = \sqrt{\beta_1 + \beta_2 \cdot \ln(X)}}$ $\boldsymbol{V = \beta_1 + \beta_2 / e^{\beta_3 \cdot X}}$
where V = speed; X = independent variable; and $\boldsymbol{\beta_i}$= regression parameters.

Equations 2-5 shows the speed models obtained considering L and $CCR_{C\_T\_C}$ as explanatory variables. As a result, loaded truck speeds can be more accurately estimated considering L, whereas $CCR_{C\text{-}T\text{-}C}$ allows a more accurate estimation of unloaded truck speeds.

$$V_{85L} = 86.57 - \frac{57.58}{e^{0.003 \cdot L}} \qquad R^2_{adj} = 0.78 \tag{2}$$

$$V_{85U} = 93.71 - \frac{41.81}{e^{0.0022 \cdot L}} \qquad R^2_{adj} = 0.69 \tag{3}$$

$$V_{85L} = 26.46 + \frac{52.72}{e^{0.0027 \cdot CCR_{C\_T\_C}}} \qquad R^2_{adj} = 0.71 \tag{4}$$

$$V_{85U} = 45.58 + \frac{44.49}{e^{0.0024 \cdot CCR_{C\_T\_C}}} \qquad R^2_{adj} = 0.77 \tag{5}$$

where V_{85L} = the 85th percentile of the speed distribution for loaded trucks (km/h); V_{85U} = the 85th percentile of the speed distribution for unloaded trucks (km/h); L = the tangent length (m); $CCR_{C\_T\_C}$ = the Curvature Change Rate of the tangent and its adjacent horizontal curves (gon/km).

As mentioned above, the grade only influences loaded truck speeds (for the grade values considered in this study), so the effect of the vertical alignment, from Equation 2 was introduced in Equation 6 to get a more accurate speed model for loaded trucks. To do this, an analysis of the residuals as a function of the grade was carried out, which showed a linear trend. Thus, the following model was proposed:

$$V_{85L} = 85.98 - \frac{58.09}{e^{0.003 \cdot L}} - 1.02 \cdot g \qquad R^2_{adj} = 0.84 \tag{6}$$

where g = grade (%);

Finally, the following regression models were calibrated based on the combination of geometric and operational variables:

$$V_{85L} = 5.70 + 1.05 \cdot V_{pc} - 0.69 \cdot g \qquad R^2_{adj} = 0.90 \tag{7}$$

$$V_{85U} = 72.95 - \frac{40.54}{e^{0.0017 \cdot L}} + 0.39 \cdot V_{pc} \qquad R^2_{adj} = 0.85 \tag{8}$$

where V_{pc} = 85th percentile of the distribution of speeds of the preceding horizontal curve (km/h).

These models resulted in a greater adjustment than those models based only on geometric variables. However, in case of not having the empirical speed, it is recommended to use the models that only depend on geometric variables (Equation 5 and 6).

15th Percentile Speed Model

Descriptive analysis

The development of the 15th percentile speed models relied on the maximum 15th percentile speed observed on every tangent.

The influence of the geometric and operational variables on 15th percentile speed was similar to those observed for the 85th percentile speed (Table 5). Specifically, the correlation coefficients associated with tangent length (L) were 0.7709 for loaded trucks and 0.7633 for unloaded trucks, whereas the correlation coefficients related to $CCR_{C\_T\_C}$ were -0.7557 and -0.7815 for loaded and unloaded trucks, respectively. Likewise, the grade of the tangent was an important and influential factor in the 15th percentile speed only for loaded trucks.

TABLE 5 Correlation analysis of the 15th percentile speed

(a) Loaded trucks

VARIABLES		V_{15}	L	V_{15pc}	R_{C1}	L_{C1}	γ_{C1}	R_{C2}	L_{C2}	γ_{C2}	$CCR_{C\_T\_C}$	CCR_{C_T}	CCR_C	CCR
V_{15}	R	1												
	Valor P													
L	R	0.7709	1											
	Valor P	7.71E-01												
V_{15pc}	R	0.9367	0.7373	1										
	Valor P	1.12E-15	9.85E-07											
R_{C1}	R	0.372	0.4271	0.4121	1									
	Valor P	0.033	0.0132	0.0172										
L_{C1}	R	0.2169	0.2589	0.2188	0.1132	1								
	Valor P	0.2253	0.1457	0.2211	0.5305									
γ_{C1}	R	-0.3291	-0.3028	-0.3343	-0.4858	0.5997	1							
	Valor P	0.0615	0.0867	0.0573	0.0042	0.0002								
R_{C2}	R	0.3263	0.2152	0.3524	0.0846	0.082	-0.1261	1						
	Valor P	0.0638	0.2292	0.0443	0.6399	0.6502	0.4844							
L_{C2}	R	0.2745	0.2444	0.2614	0.1621	0.4805	0.2203	-0.0265	1					
	Valor P	0.1221	0.1704	0.1417	0.3676	0.0047	0.2179	0.8835						
γ_{C2}	R	-0.2023	-0.0985	-0.2607	0.0885	0.0403	0.0734	-0.5869	0.5159	1				
	Valor P	0.2588	0.5854	0.1428	0.6243	0.8239	0.685	0.0003	0.0021					
$CCR_{C\_T\_C}$	R	-0.7557	-0.6365	-0.7073	-0.3811	-0.172	0.473	-0.4556	-0.1609	0.3902	1			
	Valor P	3.69E-07	0.0001	4.18E-06	0.0286	0.3385	0.0054	0.0077	0.3709	0.0248				
CCR_{C_T}	R	-0.6119	-0.5205	-0.5566	-0.5305	0.1047	0.7576	-0.175	-0.1122	0.0451	0.8346	1		
	Valor P	0.0002	0.0019	0.0008	0.0015	0.5621	3.32E-07	0.33	0.534	0.8032	1.57E-09			
CCR_C	R	-0.613	-0.4845	-0.628	-0.7484	-0.2754	0.5057	-0.3092	-0.1896	0.1712	0.7634	0.7422	1	
	Valor P	0.0001	0.0043	0.0001	5.49E-07	0.1208	0.0027	0.08	0.2906	0.3409	2.386E-07	7.63E-07		
CCR	R	-0.6404	-0.4939	-0.6328	-0.2241	-0.4061	-0.0218	-0.2889	-0.2746	0.2567	0.6607	0.3706	0.497	1
	Valor P	0.0001	0.0035	0.0001	0.2099	0.019	0.904	0.103	0.122	0.1494	2.859E-05	0.0337	0.0033	

(b) Unloaded trucks

VARIABLES		V_{15}	L	V_{15pc}	R_{C1}	L_{C1}	γ_{C1}	R_{C2}	L_{C2}	γ_{C2}	$CCR_{C\_T\_C}$	CCR_{C_T}	CCR_C	CCR
V_{15}	R	1												
	Valor P													
L	R	0.76328	1											
	Valor P	6.76E-06												
V_{15pc}	R	0.80635	0.37199	1										
	Valor P	1.13E-06	0.06709											
R_{C1}	R	0.36443	0.19571	0.45556	1									
	Valor P	0.07329	0.34846	0.02211										
L_{C1}	R	0.39919	0.23119	0.30724	0.04516	1								
	Valor P	0.04806	0.26617	0.13518	0.83027									
γ_{C1}	R	-0.24099	-0.02916	-0.41136	-0.63512	0.45521	1							
	Valor P	0.24586	0.88996	0.04106	0.00065	0.02223								
R_{C2}	R	0.74225	0.68099	0.46464	0.07384	0.08	-0.19771	1						
	Valor P	0.00002	0.00018	0.01928	0.72577	0.70385	0.34346							
L_{C2}	R	0.2249	0.16592	0.09214	-0.08533	0.40254	0.16412	0.21428	1					
	Valor P	0.27975	0.428	0.66135	0.68507	0.04605	0.43307	0.3037						
γ_{C2}	R	-0.38875	-0.38722	-0.25009	-0.2306	0.2025	0.2345	-0.53377	0.61139	1				
	Valor P	0.05479	0.05583	0.22793	0.26742	0.33166	0.2592	0.00599	0.00117					
$CCR_{C\_T\_C}$	R	-0.78147	-0.62981	-0.52796	-0.44349	-0.13392	0.38406	-0.68449	0.0773	0.70209	1			
	Valor P	3.99E-06	0.00074	0.00667	0.02638	0.52333	0.05804	0.00016	0.71343	0.00009				
CCR_{C_T}	R	-0.70088	-0.53167	-0.48316	-0.59237	-0.06649	0.58351	-0.53368	-0.04698	0.44813	0.90104	1		
	Valor P	0.0001	0.00623	0.01442	0.00181	0.75219	0.0022	0.006	0.82353	0.02467	8.20E-10			
CCR_C	R	-0.57083	-0.18233	-0.64037	-0.663	-0.28332	0.65462	-0.30439	-0.16728	0.1062	0.50705	0.68096	1	
	Valor P	0.00288	0.38304	0.00056	0.0003	0.16994	0.00038	0.13904	0.42415	0.61338	0.00968	0.00018		
CCR	R	-0.6814	-0.50633	-0.49793	-0.29195	-0.27548	0.15975	-0.50854	-0.24627	0.24997	0.61082	0.53681	0.34512	1
	Valor P	0.00018	0.0098	0.01131	0.15675	0.18259	0.44559	0.00944	0.23535	0.22816	0.00118	0.00566	0.0911	

Finally, regarding the operational variables, the 85th percentile speed of the preceding horizontal curve (V_{pc}) showed the largest correlation coefficient, 0.9367 and 0.8064 for loaded and unloaded trucks, respectively.

Modelling 15th percentile speed

Different regression models were calibrated to evaluate the geometric and operational variables influence on 15th percentile speed. For this, the same functional forms of the 85th percentile speed were studied and the R^2_{adj} was given in all regressions as goodness of fit.

As a result, Equations 9-12 show the most accurate models using the tangent length (L) and the Curvature Change Rate of the tangent and its adjacent horizontal curves ($CCR_{C\_T\_C}$) as explanatory variables. Similar to the 85th percentile speed, L allows a more accurate prediction of loaded truck speeds, whereas unloaded truck speeds were more accurately estimated considering $CCR_{C\_T\_C}$.

$$V_{15L} = 78.67 - \frac{52.32}{e^{0.0023 \cdot L}} \qquad R^2_{adj} = 0.72 \tag{9}$$

$$V_{15U} = 80.50 - \frac{36.53}{e^{0.0021 \cdot L}} \qquad R^2_{adj} = 0.61 \tag{10}$$

$$V_{85L} = 19.53 + \frac{50.33}{e^{0.0027 \cdot CCR_{C\_T\_C}}} \qquad R^2_{adj} = 0.71 \tag{11}$$

$$V_{85U} = 34.48 + \frac{42.83}{e^{0.0024 \cdot CCR_{C\_T\_C}}} \qquad R^2_{adj} = 0.71 \tag{12}$$

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).

The effect of the vertical alignment was introduced from Equation 9 in Equation 13 to enhance the speed prediction for loaded trucks. To do this, an analysis of the residuals as a function of the grade was performed, which resulted in a linear trend. Thus, the following model was proposed:

$$V_{15L} = 79.14 - \frac{50.13}{e^{0.0019 \cdot L}} - 1.07 \cdot g \qquad R^2_{adj} = 0.84 \tag{13}$$

where g = grade (%);

Related to this, it should be remembered that the previous descriptive analysis showed that the grade did not influence unloaded truck speeds for the values considered in this research (g < 6%).

Finally, different regression models were calibrated considering both geometric and operational variables:

$$V_{15L} = 4.76 + 1.04 \cdot v_{pc} - 0.65 \cdot g \qquad R^2_{adj} = 0.90 \tag{14}$$

$$V_{15U} = 64.85 - \frac{39.54}{e^{0.0017 \cdot L}} + 0.39 \cdot v_{pc} \qquad R^2_{adj} = 0.83 \tag{15}$$

where V_{pc} = 15th percentile of the distribution of speeds of the preceding horizontal curve (km/h).

As the models obtained for the 85th percentile speed, these models showed a greater adjustment than the models based on the geometric variables. However, in case of not having the empirical speed, it is recommended to use the models that only depend on geometric variables (Equation 12 and 13).

DISCUSSION

Most previous research about the analysis of heavy vehicle speeds showed a deficient data collection regarding the number of studied tangents, the number of observed vehicles, and the data collection methodology (*2, 11, 14, 22*). By contrast, this research was carried out from continuous speed profiles collected along a large number of tangents.

Although several models are available regarding the estimation of the heavy vehicle speeds on horizontal curves, the calibration of operating speed models on tangents is more complex *(9)*. This is usually associated with greater speed dispersions on tangents than on horizontal curves.

The findings of this research were compared to the previous results obtained by Llopis-Castelló et al. *(25)* on horizontal curves, since both studies were based on the same speed data collection. In this way, heavy vehicle drivers tend to keep their speeds constant around the limit speed (90 km/h) along tangents, so lower speed deviations were identified on this type of road element ($\bar{\sigma} = 1.65\ km/h$) than on horizontal curves ($\bar{\sigma} = 1.96\ km/h$). This led to speed prediction models with larger coefficients of determination than the models calibrated for horizontal curves.

The most influential variables associated to the horizontal alignment were tangent length (L) and Curvature Change Rate of the tangent and its adjacent horizontal curves ($CCR_{C\_T\_C}$). Regarding the vertical alignment, the grade did not show a significant influence on downgrades, but identified influence on upgrades for loaded trucks. This might be due to the maximum grade was 12% for loaded truck speeds, whereas this value was equal to 6% for unloaded truck speeds. In addition, the speed of the preceding horizontal curve (V_{pc}) also showed an important influence on truck speeds. This was consistent with the results obtained in previous studies *(10, 11, 12, 14)*.

The calibrated models developed in this research were also compared with the speed profiles proposed by the different geometric design guidelines. Specifically, the AASHTO *(6)* defines truck speeds along upgrades as a function of the weight-to-power ratio (120 kg/kW), the beginning speed (20 - 100 km/h), the distance (0 - 4,000 m), and the grade (-5 % - +8 %).

These speed profiles show a speed difference of 65 km/h between an upgrade section of 1% and another of 8% for a heavy truck with a WPR equal to 120 kg/kW on tangents longer than 500 m. However, this speed difference is equal to 10 km/h considering the 85th percentile speed model calibrated in this study for loaded trucks. This might be due to differences in mechanical characteristics of the vehicles, driver behavior, and road geometry between the United States and Spain. However, it should also be noted that the speed profiles proposed by the AASHTO were carried out between the 40's and the 80's.

Finally, the differences between passenger car speeds and unloaded truck speeds on tangents were analyzed (Figure 4). For this, the speed model for passenger cars proposed by Pérez-Zuriaga et al. *(28)* was considered because these models were calibrated in the same region following the same methodology of data collection:

$$V_{85} = V_{pc} + (1 - e^{-\gamma \cdot L}) \cdot (V_{des} - V_{pc}) \quad (16)$$

where V_{85} = 85th percentile of the distribution of speeds for passenger cars (km/h); V_{pc} = 85th percentile speed of the preceding horizontal curve (km/h):

$V_{pc} = 97.4254 - 3310.94/R$; $\gamma = 0.00135 + (R - 100) \cdot 7.00625 \cdot 10^{-6}$; $L =$ tangent length (m); V_{85des} = desired speed (110 km/h); and R = radius of the preceding horizonal curve (m).

As a conclusion, the speed difference between both types of vehicle increases as the radius increases and the tangent length decreases (Figure 4). This is mainly due to passenger cars can accelerate more quickly than heavy vehicles. These differences are prone to produce traffic conflicts between heavy vehicles and passenger cars such as rear-end collisions.

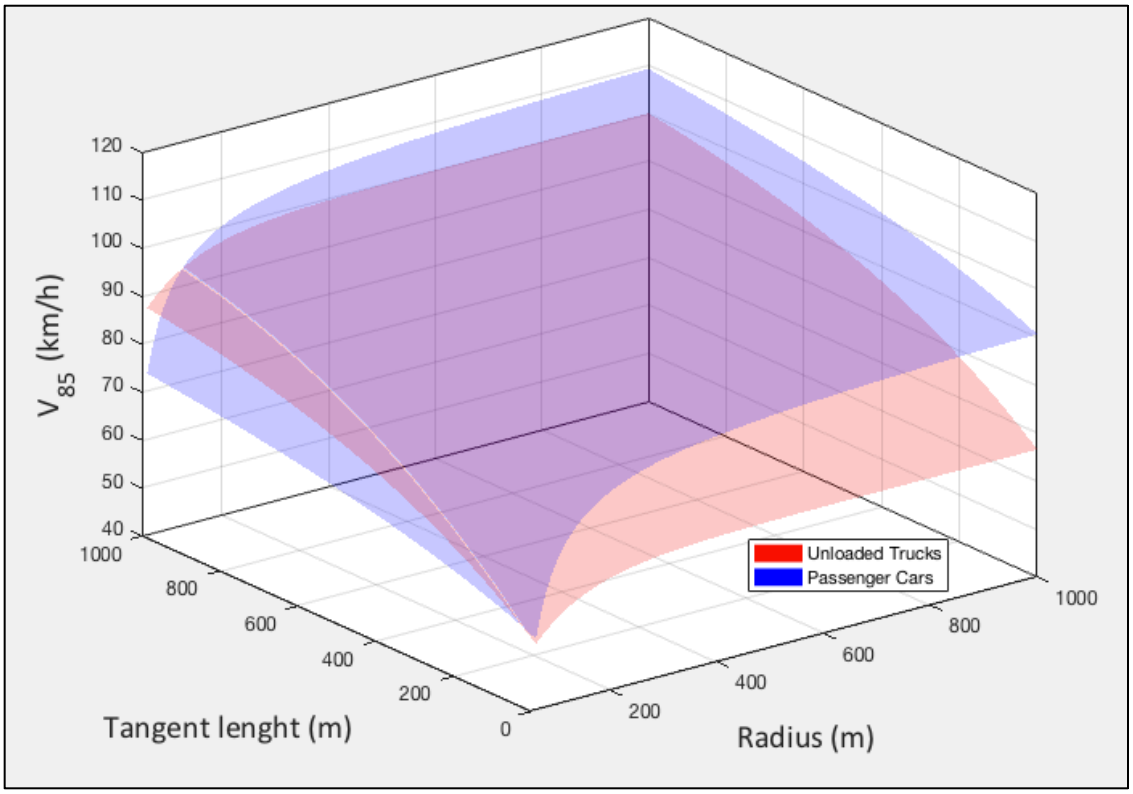


FIGURE 4 Comparison between 85th percentile speed of unloaded trucks and passenger cars.

It should be highlighted that the speed of heavy vehicles is greater than the speed of passenger cars for the combination of radii lower than 100 m and long tangents. This is because the developed models were not calibrated considering these conditions, which are difficult to find in existing highways.

Although the speed difference between loaded trucks and passenger cars is greater than the speed difference between unloaded trucks and passenger cars, the previous described trends can also be attributed to the comparison between loaded trucks and passenger cars.

CONCLUSIONS AND FURTHER RESEARCH

In Spain, the most of the traffic accidents involving a heavy vehicle occur on two-lane rural roads. This research shows several models for estimating the 85th and 15th percentile speed for heavy vehicles on tangent sections of two-lane rural roads, which include geometric and operational variables as explanatory variables. Besides, was analyzed of the 15th percentile speed, because the lower percentiles are prone to produce traffic conflicts between heavy vehicles and passenger cars such as rear-end crashes. For this purpose, continuous speed profiles were collected through Global Positioning System (GPS) tracking devices

The truck speeds mainly depend on the weight-to-power ratio (WPR). Related to this, two different patterns were found which were associated to unloaded (average value 43 kg/kW) and loaded (average value 120 kg/kW) trucks.

The most influential variables on loaded truck speeds were the speed of the preceding horizontal curve and the longitudinal grade of the tangent, whereas unloaded truck speeds were significantly influenced by the length of the tangent and the speed of the preceding horizontal curve. Both loaded and unloaded truck speeds increase as the speed of the preceding horizontal curve increases. Additionally, loaded truck speeds decrease as the grade increases, whereas unloaded truck speeds increase with tangent length.

The use of the speed models developed in this research are only recommended on Spanish two-lane rural roads, since great differences regarding mechanical characteristics of the vehicles, driver behavior, and road geometry exist among countries.

Additionally, the developed 85th percentile speed models for unloaded heavy vehicles were compared with the 85th percentile speed models for passenger cars proposed by Pérez-Zuriaga et al. *(28)*. As a result, the speed difference between both types of vehicle increases as the radius of the preceding horizontal curve or the grade of the tangent increases and the length of the tangent decreases.

In this manner, the speed models developed in this research are an important part to build the new operating speed profiles for trucks, it will allow highway engineers to include the interaction between heavy vehicles and passenger cars in road safety analysis.

Finally, the next step will be the analysis of tangent-to-curve speed variations and the calibration of new acceleration and deceleration rate models. To do this, the continuous speed profiles collected for this research will be used.

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AUTHOR CONTRIBUTIONS

The authors confirm contributions to the paper as follows:

- Study conception and design: Llopis-Castelló, D. and García, A.
- Data collection: Llopis-Castelló, D. and García, A.
- Analysis and interpretation of results: González-Hernández, B., Llopis-Castelló, D.
- and García, A.
- Draft manuscript preparation: González-Hernández, B. and Llopis-Castelló, D.

All authors reviewed the results and approved the final version of the manuscript.

REFERENCES

1. WHO. Global status report on road safety 2015. World Health Organization, 2015.
2. Donnell, E., Ni, Y., Adolini, M., & Elefteriadou, L. Speed prediction models for trucks on two-lane rural highways. *Transportation Research Record: Journal of the Transportation Research Board*, 2001, 1751: 44-55.

3. Harwood, D. W. Review of truck characteristics as factors in roadway design (Vol. 505). Transportation Research Board, 2003.
4. Leisch, J. E., & Leisch, J. P. New concepts in design-speed application. . *Transportation Research Record: Journal of the Transportation Research Board*, 1977, 631: 4-14.
5. Fancher, P. S., & Campbell, K. L. *Vehicle characteristics Affecting safety and truck size and weight regulations*. U. S. Deparment of Transportation, 1995, Washington, DC.
6. AASHTO (American Association of State Highway and Transportation Officials). *A policy on geometric design of highway and streets*. AASHTO, 2011, Washington, DC.
7. Walton, C. M., & Lee, C. E. Characteristics of trucks operating on grades. . *Transportation Research Record: Journal of the Transportation Research Board*, 1977, 631: 23-30.
8. Polus A., Pollatsceck M. A., Mattar-Habib C., & Jarroush J. An enhanced, integrated, desing consistency model for both level and mountainous highways and its relationship to safety. *Road and Transport Research*, 2004, 14(4): 13-26.
9. Jacob, A., & Anjaneyulu, M. V. L. R. Operating speed of different classes of vehicles at horizontal curves on two-lane rural highways. *Journal of Transportation Engineering*, 2012, 139(3): 287-294.
10. Lamm, R., Choueiri, E. M., Hayward, J. C., & Pauluri, A. Possible design procedures to promote design consistency in highway geometric design of two-lane rural roads. *Transportation Research Record: Journal of the Transportation Research Board*, 1988, 1195: 111-122.
11. Al-Masaeid, H. R., Hamed, M., Aboul-Ela, M., & Ghannam, A. G. Consistency of horizontal alignment for diferent vehicle classes. *Transportation Research Record: Journal of the Transportation Research Board*, 1995, 1500:178-183.
12. Otteson, L. J., & Krammes, R. A. Speed profile model for a design consistency evaluation procedure in the United States. *Transportation Research Record: Journal of the Transportation Research Board*, 2000, 1701: 76-85.
13. Polus, A., Fitzpatrick, K., & Fambro, D. B. Predicting operating speed on tagent sections of two-lane rural highways. *Transportation Research Record: Journal of the Transportation Research Board*, 2000 , 1737: 50-57.
14. Boroujerdian, A. M., Seyedabrishami, E., & Akbarpour, H. Analysis of geometric design impacts on vehicle operating speed on two-lane rural roads. *Procedia engineering*, 2016, 161: 1144-1151.
15. Bester, C. Truck speed profiles. *Transportation Research Record: Journal of the Transportation Research Board*, 2000, 1701: 111-115.
16. Lan, C. J., & Menendez, M. Truck speed profile models for critical length of grade. *Journal of Transportation Engineering*, 2003, 129(4): 408-419.
17. Rakha, H., & Yu, B. Truck performance curves reflective of truck and pavement characteristics. *Journal of Transportation Engineering*, 2004, 130(6): 753-767.
18. Echaveguren, T., & Carrasco, D. Estimación de longitud crítica en pendientes ascendentes en caminos bidireccionales. *Revista ingeniería de construcción*, 2015, 30(1): 5-16.
19. Ministerio de Fomento. *Instrucción de Carreteras, Norma 3.1-I.C.*, 2016, Spain.

20. Instituto Nacional de Vías (INVIAS). *Manual de diseño geométrico de Carreteras*, 2008, Colombia.
21. Ministerio de Obras Públicas. *Instrucciones y criterios de diseño. Manual de Carreteras*, Volumen 3, 2014, Chile.
22. Arellano, D., Echaveguren, T., & Vargas-Tejada, S. A model of truck speed profiles on short upward slopes. *Proceedings of the Institution of Civil Engineers – Transport*, 2015, 168(5): 475-483.
23. Saifizul, A. A., Yamanaka, H., & Karim, M. R. Empirical analysis of gross vehicle weight and free flow speed and consideration on its relation with differential speed limit. *Accident Analysis & Prevention*, 2011, 43(3): 1068-1073.
24. Morris, C. M., & Donnell, E. T. Passenger Car and TruckOperating Speed Models on Multilane Highways with combinations of Horizontal Curves ans Steep Grades. *Journal of Transportation Engineering,* 2014, 140(11), 04014058.
25. Llopis-Castelló, D., González-Hernández, B., Pérez-Zuriaga, A.M. & García, A. Speed prediction models for trucks on horizontal curves of two-lane rural roads. *Transportation Research Record: Journal of the Transportation Research Board*, 2018, https://doi.org/10.1177/0361198118776111
26. Camacho‐Torregrosa, F. J., Pérez‐Zuriaga, A. M., Campoy‐Ungría, J. M., García, A., & Tarko, A. P. Use of Heading Direction for Recreating the Horizontal Alignment of an Existing Road. *Computer‐Aided Civil and Infrastructure Engineering*, 2015, 30(4): 282-299.
27. Zuriaga, A., García, A., Torregrosa, F., & D'Attoma, P. Modeling operating speed and deceleration on two-lane rural roads with global positioning system data. *Transportation Research Record: Journal of the Transportation Research Board*, 2010, 2171: 11-20.
28. Pérez-Zuriaga, A. M., F. J. Camacho-Torregrosa, A. García, and J. M. Campoy-Ungría. Application of global positioning system and questionnaires data for the study of driver behaviour on two-lane rural roads. *IET Intelligent Transport Systems*, 2013, 7(2): 182-189.