Estimación de longitud crítica en pendientes ascendentes en caminos bidireccionales

Estimation of critical length in ascending grades of two-lane rural roads

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Resumen

La pendiente ascendente máxima en un camino bidireccional se utiliza como criterio para determinar la necesidad de pistas de ascenso para vehículos pesados. Para ello, se necesita contar con un perfil de velocidad que depende de la inclinación y longitud de la pendiente y de las características dinámicas, físicas y mecánicas de los vehículos pesados. La normativa Chilena utiliza un perfil de velocidad para un vehículo tipo de relación peso/potencia de 120 kg/kW y una velocidad de entrada a la pendiente de 88 km/h. Este único modelo impide analizar casos en que la velocidad de entrada es significativamente distinta o casos en que el vehículo de diseño puede ser distinto debido a condiciones locales y por tanto no permite estimar valores realistas de pendientes máximas. En ese trabajo se simuló modelos de velocidad basados en aceleraciones y en equilibrio de fuerzas para proponer nuevos valores de pendientes máximas considerando razones peso/potencia entre 120 y 263 kg/kW, velocidades de entrada a la pendiente entre 80 y 100 km/h y reducciones admisibles de velocidad entre 10 y 30 km/h. Se obtuvieron diversos valores de longitud máxima de pendiente, lo cual permite a los diseñadores contar con más opciones para proyectar pendientes ascendentes.

Palabras claves: Velocidad, perfil de velocidad, pendiente ascendente máxima, vehículo pesado, razón peso/potencia

Abstract

The critical length of grade on two-lane rural roads is used as criterion to assess the need of ascending lanes for heavy vehicles. To estimate it, a speed profile is needed, which depends on the road's grade and length, and on the physical, dynamic and mechanical characteristics of heavy vehicles. The Chilean standard uses a speed profile for a design truck that have a weight-to-power ratio of 120 kg/kW and an entrance speed of 88 km/h. This unique model prevents from studying cases in which the entrance speed can be different or in which the design vehicle is significantly different to the design speed of standards due to local conditions and consequently, does not allow estimating realistic critical lengths of grades. In this work, speed profiles models based on acceleration and force equilibrium were simulated, considering weight-to-power ratios between 120 and 263 kg/kW, entrance speeds between 80 and 100 km/h. Several values of critical lengths of grades were estimated, which offers engineers more options when designing ascending slopes.

Keywords: Speed, speed profile, critical length of grade, heavy vehicle, weight-to-power ratio

1. Introduction

Speed profiles describe how the operating speed of a heavy-vehicle varies as it drives up a grade. In ascending grades, design instructions use them to assess the need of projecting ascending grades under service level and security criteria, or to define the maximum slope and length of an ascending grade in order to omit an ascending lane. The main variables which explain the speed reduction are the slope and length of the grade, the vehicle weight-to-power ratio (WPR) and the speed at which the vehicle enters the grade (Fitch, 1994). For the same ascending grade geometry, the performance of similar heavy vehicles, related to WPR, may be completely different depending on the speed entrance. Likewise, considering the wide range WPR for vehicles, the performance may also be different, so in practice, each heavy vehicle will have a unique speed profile.

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Standards use speed profiles considering a design vehicle, with a typical power, with a unique entrance speed to the grade, for uniform slopes up to 10% and lengths of grades that vary between 0 and 6 km (Arellano et al., 2014). In Chile, design instructions define the maximum longitudinal grades based on a standard speed profile adopted from the US' standards. This speed profile considers a design vehicle whose WPR is 120 kg/kW, a unique entrance speed of 88 km/h, an inclination range between 1% and 8% and a length of grade between 0 and 3 km (MOP, 2014).

The Chilean standard that uses only one speed profile does not allow considering diverse design conditions, as for example the effect of elements for speed reduction that limit the entrance speed or, on the contrary, wide courses that encourage drivers to use higher operation speeds. Likewise, the WPR proposed in the current Chilean Roadways Handbook does not necessarily represent the characteristics of the heavy weight vehicles fleet. Arellano et al. (2014) indirectly determined that it varies between 95 and 609 kg/kW, with predominance between 100 and 160 kg/kW. In consequence, relying on speed profiles, models and more entrance speed options of design vehicles which are more similar to the current fleet, offers a greater variety of design conditions that, in the end, allows improving the geometric designs.

Therefore, this study proposes new truck speed profiles for ascending grades, using different WPR and entrance speed combinations. Based on these profiles new critical length charts are proposed to define the critical longitudinal of grades for two-lane roads.

Speed theoretical models and road geometric design standards were analyzed that included speed profiles for the design of ascending grades. A speed theoretical model was simulated based on Bester (2000), and Rakha and Yu (2004) models. From these simulated models, nine speed profiles were obtained for the combinations of three WPR (120, 150 and 263 kg/kW) and three grade entrance speeds (80, 90 and 100 km/h). Using these profiles, nine new charts with the critical length of grade were prepared for speed acceptable reductions (ΔV) between 10 and 30 km/h and for each WPR and entrance speeds. Finally, the results obtained were compared with the critical length values recommended by the Chilean Roadways Handbook and the American design standard.

2. Speed models in ascending grades

Figure 1 outlines two types of speed profiles depending on the sign of the uniform slope.

Figura 1. Perfil teórico de velocidad en pendientes uniformes (Arellano et al., 2014)

Figure 1. Theoretical speed profile in uniform slopes (Arellano et al., 2014)

In ascending slopes, speed decreases from an initial value (point B) to a balance speed (point D) (also known as crawl speed), which remains more or less constant until the end of the uniform slope (F). This deceleration is due to the increase of the resistive forces in the face of the forces provided by the engine (Rakha and Yu, 2004) reaching to a null value (point C). The balance speed corresponds to the maximum speed that a truck may attain travelling in a longitudinal slope. The magnitude and distance at which this speed is reached depend on (Archilla and Fernández de Cieza, 1996): the length of the ascending section, the slope of the ascending grade, the vehicle WPR, the height above sea level, the vehicle initial speed, the presence of horizontal curves and the lateral restrictions.

Models that explain this behavior are classified in two categories (Arellano et al., 2014): those based on the dynamic performance and those based on the cinematic performance. Dynamic models describe the balance between the tractive force (F_T), the aerodynamic force (F_A), the rolling resistance (F_R) and the resistance associated to the weight (F_G). When the tractive force is greater than the sum of resistances, the remaining force (Ma) allows the movement (section AC or BD in Figure 1). When this remaining force is null ($Ma=0$), the vehicle travels at the balance speed (section CE and DF in Figure 1). In this category of models, those from Lee and Lee (2000), and Rakha et al. (2001) are the most important.

Equation 1 shows the Rakha et al. (2001) model based on the force balance. Equation 2 shows the discrete solution of the differential equation: $\ddot{x}=f(\dot{x}, x)$ that allows obtaining the speed profile in function of the distance based on Equation 1. P (N) corresponds to the heavy vehicle effective power, a (m/s^2) is the acceleration, V (km/h) is the speed, F_{MAX} (eN) is the maximum power, m (kg) is the mass, g (m/s^2) is the gravity acceleration, i (%) is the grade slope, t_i (s) is a time instant in which the vehicle is in the position x_i , a corresponds to the acceleration, Δt (s) is the integration time step and α_i are the model's coefficients. The detailed expression can be read in Rakha and Yu (2004).

$$\frac{dV}{dt} = \frac{F_T - R_A - R_R - R_G}{m} = \frac{\max\left\{\alpha_1 \frac{P}{V}, F_{MAX}\right\} - \alpha_2 V^2 - \alpha_3 (\alpha_4 + \alpha_5 V)m - mgi}{m} \quad (1)$$

$$\frac{dV(t_i)}{dt} = \frac{F_T(t_i) - R_A(t_i) - R_R(t_i) - R_G(t_i)}{m} ; \quad \left\{ \begin{array}{l} \frac{dV(t_i)}{dt} \\ \frac{dx(t_i)}{dt} \end{array} \right\} = \left\{ \begin{array}{l} a(t_i) \\ V(t_i) \end{array} \right\}$$

$$V(t_i) = V(t_{i-1}) + a(t_{i-1})\Delta t$$

$$x(t_i) = x(t_{i-1}) + V(t_{i-1})\Delta t \quad (2)$$

Cinematic models create the speed profile based on the following variables: displacement, speed and acceleration. The acceleration was modelled using lineal specifications such as that of Bester (2000) (Equation 3) or non-linear such as that of Lan and Menendez (2003).

$$a = \alpha + \beta V - gi \frac{m}{m_e} \quad (3)$$

In Chile, Arellano et al. (2014) evaluated Bester's acceleration model (2000) (Equation 3) based on speed and position data obtained through a GPS device, for a WPR range between 100 and 160 kg/kW and an entrance speed of 93 km/h, to obtain the speed profiles. They determined that the entrance speed used in the Chilean Roadways Handbook (MOP, 2014) corresponds to percentile 82 of the speed distribution observed in the field and that the balance speed resulted 1.15 times greater than that predicted by the model described in MOP (2014).

3. Critical length in ascending grades

The critical length of an ascending grade is the maximum length over which a heavy vehicle travels without reducing its speed, in a certain amount, in respect to the slope entrance speed. The decrease in the operation speed of heavy vehicles increases the risk of accidents in two-lane roads, because light vehicles are compelled to surpass them. Glennon (1970) demonstrated that, independently of the media speed value of the road, the more a vehicle deviates from this media speed, the more there is a probability of suffering an accident. Figure 2 graphically shows how the accident rate varies when a heavy vehicle reduces the speed on a grade.

In case it is not possible to limit the grade to its critical length, there is the option of designing an exclusive ascending lane for heavy vehicle. To estimate the critical length, all possible combinations are traced for: the grade (i in %), the slope length (L , in m), the distance from the beginning of the slope, where the vehicle reduces its speed ΔV km/h. To obtain this chart, it is necessary to have profile speeds such as those described in section 2 of this paper.

Figura 2. Accidentes en función de la reducción de velocidad (Glennon, 1970)

Figure 2. Accidents based on speed reduction (Glennon, 1970)

Figure 3a shows the design graph used by the US design recommendations and Figure 3b shows that of the Chilean standards calculated from the speed profile model described by the Transportation Research Board (TRB) (1994).

Figura 3. Gráficas de cálculo de longitud crítica (AASHTO, 2011; MOP, 2014)

Figure 3. Charts for the estimation of critical length (AASHTO, 2011; MOP, 2014)

Currently, the AASHTO standard (2011) establishes a reduction of 15 km/h on the maximum speed, which corresponds to 500 accidents/10⁸ km approximately. The Chilean standard adopts a reduction of 40 km/h in the maximum speed, which implies a greater accident potential.

4. Calculation of the new values for critical speed in grades

The calculation of the new critical length values was developed in three stages. In the first one, the analysis conditions were defined; in the second one, speed profiles were simulated and in the third one, the critical length values were calculated.

4.1 Conditions for calculation

For this purpose, combinations of the entrance speed to the grade, WPR and the geometry of the grade profile were considered. The entrance speed to the grade was chosen considering project speeds associated to each design category defined by MOP (2014). The speeds used were 80, 90 and 10 km/h, which correspond to the Primary and Collector road categories, both for two-lane roads. This speed range also considers the types of plain, undulating and mountainous ground. Speeds associated to the upper categories were not considered, assuming that, in general, they correspond to roads with separated lanes and less inclined slopes, which due to their design, do not induce the same phenomena as two-lane roads do. Instead, lower categories lead to consider entrance speeds lower enough so the difference with respect to the balance speed is lower than the critical values; thus, so the accident rate is not as important as in the study cases. In relation to the WPR, three values were considered: 120, 150 and 263 kg/kW. The first corresponds to the one used at the present by MOP (2014); the second, is based on the results obtained by the Arellano et al. study (2014) and the third corresponds to heavy vehicles with a total gross weight of 90 tons, which are high-tonnage vehicles according to Díaz (2012). The latter was analyzed assuming that they may be used in Chile to reduce transportation costs. Geometry was specified considering the standards established by MOP (2014) for the profile geometric design: a slope range between 1 and 8%, and a slope maximum length of 3 km.

4.2 Speed profile simulation

Rakha et al. model (2001) was simulated for each entrance speed, WPR and geometry combination using Equations 1 and 2. Afterwards, the Bester's model (2000) was used to estimate α and β values. Both models adjusted when the root mean square error (RMSE) value was under 0.5 km/h. Then, the values of $\alpha = 0.948 \pm 0.17$ and $\beta = 0.043 \pm 0.01$ were obtained. The variability of these coefficients is due to the combinations of the entrance speed values, WPR and geometry used. The α values depend on the entrance speed, the WPR and on the geometry, in consequence, they are unique for each value combination of these variables. Considering the lower variability of β , a value of 0.043 was assumed. The α values used correspond to those calculated for each combination of geometry, WPR and entrance speed. With these parameters, 9 speed profiles were reconstructed based on distance using the Bester's model (2000) calibration procedure described in Arellano et al. (2014). Figure 4 shows the simulated profiles.

4.3 Estimation of the critical length values

Based on the speed profiles in Figure 4, the new critical length values were calculated for speed variations beginning from an entrance speed of 10 and 30 km/h each 5 km/h. Results are graphically summarized in Figure 5.

Figura 4. Perfiles de velocidad generados a partir de los modelos de Bester (2000) y Rakha et al. (2001)

Figure 4. Speed profiles generated with the Bester (2000) and Rakha et al. (2001) models

Figura 5. Gráficos para el cálculo de longitud crítica en base a perfiles de velocidad simulados
Figure 5. Graphs for the estimation of the critical length based on simulated speed profiles

Table 1 shows the critical length values for speed differences of 15 km/h and 25 km/h, and different entrance speeds and WPRs.

Tabla 1. Longitudes críticas de pendiente (en m)**Table 1.** Slope Critical Lengths (in m)

RPP=120 kg/kW establecido en Manual de Carreteras/ WPR=120 kg/kW determined by the Roadways Handbook						
i%	V ₀ = 80 km/h		V ₀ = 90 km/h		V ₀ = 100 km/h	
	$\Delta V=15\text{ km/h}$	$\Delta V=25\text{ km/h}$	$\Delta V=15\text{ km/h}$	$\Delta V=25\text{ km/h}$	$\Delta V=15\text{ km/h}$	$\Delta V=25\text{ km/h}$
3	-	-	604	-	372	832
4	676	-	370	898	278	544
5	370	1130	268	538	224	412
6	260	540	212	394	186	332
7	200	378	174	314	160	280
8	164	294	150	260	140	242
RPP=150 kg/kW según Arellano et al. (2014)/ WPR=150 kg/kW according to Arellano et al. (2014)						
i%	V ₀ = 80 km/h		V ₀ = 90 km/h		V ₀ = 100 km/h	
	$\Delta V=15\text{ km/h}$	$\Delta V=25\text{ km/h}$	$\Delta V=15\text{ km/h}$	$\Delta V=25\text{ km/h}$	$\Delta V=15\text{ km/h}$	$\Delta V=25\text{ km/h}$
3	542	-	336	746	262	500
4	330	812	250	488	212	386
5	240	478	200	368	178	316
6	188	350	168	298	154	268
7	156	278	144	250	136	232
8	132	230	126	216	120	206
RPP=263 kg/kW correspondiente a vehículos de alto tonelaje/ WPR=263 kg/kW for high-tonnage vehicles						
i%	V ₀ = 80 km/h		V ₀ = 90 km/h		V ₀ = 100 km/h	
	$\Delta V=15\text{ km/h}$	$\Delta V=25\text{ km/h}$	$\Delta V=15\text{ km/h}$	$\Delta V=25\text{ km/h}$	$\Delta V=15\text{ km/h}$	$\Delta V=25\text{ km/h}$
3	176	322	160	282	148	258
4	148	260	138	238	132	224
5	126	218	122	208	118	200
6	112	188	108	184	106	180
7	98	166	98	164	98	162
8	90	148	90	148	90	150

4.4 Discussion of Results

From speed profiles in Figure 4, it can be observed that as WPR increases, vehicle climbing speed decreases, so the critical length inevitable proves to be lower, as it is shown in Figure 5 and in Table 1. For the high-tonnage configuration (WPR=263 kg/kW), the reduction of the critical length is located between 40 and 70 % with regard to the design vehicle currently used by the Roadways Handbook (WPR=120 kg/kW). This implies that, in almost the complete range of grades, the high-tonnage configuration requires ascending lanes when the slope length is greater than the range comprised between 150 and 320 m, $\Delta V=25$ km/h is considered as a reference. In the case of the design vehicle used by the current standard, that range is set between 240 m and 1130 m, and in the case of the representative vehicle considered by Arellano et al. (2014), the range is found between 200 and 810 m.

Tables 2 and 3 gather the critical length values of the AASHTO standards (2011) and the Roadways Handbook (MOP, 2014) as well as the results of this work, the WPR and similar entrance speeds for the same design vehicle.

Table 2 shows that for speed reductions of 15 km/h and 25 km/h, the proposed model exhibits lower critical lengths than those established in the AASHTO standards. For $\Delta V=15$ km/h, differences vary from 42% for grades of 3%, to 16 % for grades of 8%. For $\Delta V=25$ km/h, differences vary between 38% for grades of 3%, to 11% for grades of 8%. That implies that when using the AASHTO model in Chile, the critical length is being over-estimated and in consequence, the need of ascending lanes is being under-estimated.

Tabla 2. Valores de longitud critica en pendiente de AASHTO (2011) y este estudio

Table 2. Critical length values of grades from AASHTO (2011) and this study

i%	AASHTO (2011)		Este estudio/This study	
	$\Delta V = 15$ km/h	$\Delta V = 25$ km/h	$\Delta V = 15$ km/h	$\Delta V = 25$ km/h
3	500	900	288	556
4	350	600	234	428
5	270	450	196	350
6	220	360	170	296
7	175	300	150	258
8	160	255	134	228

In Table 3, it can be observed that for $\Delta V=40$ km/h and grades between 3% and 5%, the proposal of this paper does not restrict the grade lengths, so it is not possible to make comparisons. For $\Delta V=40$ km/h and grades between 6 and 8%, critical lengths were higher than those given by the Roadways Handbook. The differences vary from 140% for a grade of 6%, 57% for a grade of 7% and 36% for a grade of 8%. For $\Delta V=24$ km/h, the proposed values are higher than those given by the Roadway Handbook. The differences vary from 21% for a grade of 8% to 6% for a grade of 4%.

Tabla 3. Valores de longitud critica en pendiente de MOP (2014) y este estudio

Table 3. Critical Length values of grades from MOP (2014) and this study

i%	MOP (2014)		Este estudio/This study	
	$\Delta V = 24$ km/h	$\Delta V = 40$ km/h	$\Delta V = 24$ km/h	$\Delta V = 40$ km/h
3	1100	-	-	-
4	590	1800	970	-
5	380	700	542	-
6	310	510	390	1218
7	260	420	308	658
8	210	360	254	490

5. Conclusions

The objective of this work was to propose new values for critical length of grades, based on simulated new speed profiles and considering a wider variety of grade entrance speeds and weight-to-power ratios.

The results obtained show that the critical length of grades depends on the speed profile, which at the same time depends on the profile geometry, the weight-to-power ratio and grade entrance speed of the vehicle. As the last two variables depend on the heavy-vehicle fleet and the vehicle operation, it is not recommendable to establish only one group of values for a design vehicle, but rather a group of values that accounts for the variability of speed entrance, WPR and vehicle fleet.

The work analyzed the case of high-tonnage configurations ($WPR=263$ kg/kW). This configuration which has been adopted in some Latin American countries in order to generate savings in transportation costs. The work demonstrates that for these configurations, the need of ascending lanes is substantially greater (between 40 and 60% greater) than for conventional heavy vehicles; therefore its eventual use will necessarily require an investment on ascending lanes for safety reasons.

Compared with the Chilean Roadways Handbook, and using the same design vehicle, the critical length values proposed in this paper are higher. On average, for $\Delta V=24$ km/h and $\Delta V = 40$ km/h, the proposed model gives values 35 and 77% higher. It is recommendable to use the values proposed in this study, since they consider more options for the entrance speed, they use a design vehicle similar to those travelling on Chilean roadways and consider a more rigorous speed reduction criterion that results in a reduction of accident risks.

Although Arellano et al. calibrated a model in Chile, in order to increase the model's generality it is necessary to characterize heavy vehicles with respect to their weight-to-power ratio. Therefore, it is necessary to calibrate the Bester's model in plain ground to estimate the movement in relation to the weight-to-power ratio in motion and not in a static way or motionless.

Another aspect that should be considered to improve the estimation of critical length of grades is the validation of Glennon's model, since it allows establishing, in a more accurate way, which are the tolerable values for accident risk and from this assessment to establish the speed decreasing values that will be used to estimate the critical length. Specially, in this work the values used were those recommended worldwide by the geometric design standards ($\Delta V=15$ km/h and $\Delta V = 25$ km/h) and those used in the Roadways Handbook mainly for comparative purposes ($\Delta V=24$ km/h and $\Delta V = 40$ km/h).

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