Evaluación de la necesidad de lechos de frenado en pendientes descendentes usando principios de confiabilidad

Assesment the arrestor bed needs in downwards based on reliability principles

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Resumen

En pendientes descendentes prolongadas existe la posibilidad que los vehículos pesados sufran el corte de frenos. En tal caso, el conductor pierde el control de la velocidad de descenso del vehículo, incrementándose hasta valores superiores a los 120 km/h, caso en el cual el riesgo de accidentes aumenta. Los lechos de frenado son dispositivos que permiten contener los vehículos pesados fuera de control. En este trabajo se propone un método para determinar la necesidad de emplazar un lecho de frenado en una pendiente descendente, considerando el perfil de temperatura del sistema de frenos de los vehículos pesados, su peso y la geometría de la pendiente. Estos elementos se conjugan en un criterio para el diseño y otro para la operación. El primero evalúa la geometría en función de la velocidad de entrada. El segundo calcula un índice de peligrosidad basado en los principios de la confiabilidad para determinar la probabilidad de falla. Se presentan ejemplos de aplicación para configuraciones de carga convencionales (45 toneladas) y de alto tonelaje (61 y 75 toneladas), con diferentes potencias de frenado. Los criterios propuestos proporcionan mayor flexibilidad al diseñador, permiten clasificar la peligrosidad de las pendientes y evaluar la necesidad de proyectar lechos de frenado.

Palabras Clave: Lecho de frenado, vehículo pesado, pendiente descendente, confiabilidad

Abstract

In steeped downwards there exist the probability that heavy trucks were affected of cut brakes. In this situation, driver loses speed control downward, increasing speed up to 120 km/h or more and the crash risk increases. The arrestor beds are devices that provide contention to out-of-control trucks in downwards. This paper proposes a method to estimate the need of arrestor beds, based in the brake temperature profile, the weight of heavy trucks and the road geometry. The method is applicable in the geometric design and for road operation. In the first case, geometry is assessed using the entrance speed at the downward. In the second case, a dangerousness index is proposed based in reliability principles to estimate failure probability. Examples are presented considering trucks of 45, 60 and 70 tons of weight with different brake power. The index and criteria proposed are flexible and permitted to the designer to estimate the dangerousness of downwards and to design arrestor beds.

Keywords: Arrestor beds, heavy vehicles, downward, reliability

1. Introduction

Arrestor beds are containment systems placed at the sides of roads crossing steeped downgrades, where braking systems failures of heavy weight vehicles are likely to take place. From the point of view of roads design, three questions shall be answered when deciding whether implementing arrestor beds: Are they needed? If so, where would they be installed? What is the length required?

So as to answer such questions, it is necessary to consider downgrades geometrical design and the mechanical characteristics of heavy weight vehicles. It is necessary to connect their weight, engine power, braking power, and kind of braking system with downhill speed, length and slope inclination.

The first two questions are not easy to answer at all. In fact, they are one of the main weaknesses of the existing roads design regulations and guidelines. While the third question is answered by most regulations by means of speed profiles, based on a closed system energetic balance.

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This research is focused on the first question. Is the arrestor bed implementation required? Taking into account that most roads design regulations and guidelines employ reactive guidelines (after accidents had already taken place due to brakes failures); such guidelines isolate the problem from the kind of truck, assuming behavior indexes from geometrical nature only. Both approaches are actually weak, as far as they do not include heavy weight vehicles mechanical features or their behavior while travelling steeped downgrades.

Motor truck engineering provides models on braking systems behavior, as well as vehicles performances based on mechanical models. Such models estimate the temperature of the braking system in function of the balance of tractive forces. Based on those models, this research proposes a practical procedure to determine the implementation of arrestor beds and to recognize potentially dangerous downgrades.

Consequently, a calculation method based on the temperatures evolution of braking system is employed, by taking into account vehicles total gross weight, operation speed, braking system power, engine power and braking system type. The proposed method is able to determine when brake failures are likely to take place or not, on a given downgrade. Therefore, it is capable of determining when the arrestor bed implementation is required.

Afterwards, a characterization of heavy weight vehicles existing in the Chilean market is developed, by including heavy weight vehicles up to 45-tons total gross weight. Both inputs are considered to develop a design criterion for different tonnages and operation speed so that to decide when implementing arrestor beds areas at steeped downhill roads.

Cases of study are analyzed considering heavy weight vehicles with conventional braking systems and combinations of high tonnage vehicles (up to 75 tons) owning diverse auxiliary braking systems. Finally, a comparison is made using the design criterion currently employed by design guidelines.

2. Braking on steeped downgrades

A braking process is intended to slow down a vehicle speed without necessarily decreasing its speed down to zero. While braking, the system reduces the speed by transforming the kinetic energy into a certain amount of acoustic energy, which is dissipated as noise and; into a larger amount of thermal energy which is dissipated as heat.

2.1 Braking on steeped downgrades

On steeped downgrades, the driver brakes to maintain a constant vehicle's speed, without affecting safety, stability and driving steering. In such situation, the vehicle has a power energy which is proportional to its mass and position on the downgrade. This energy is transformed into kinetic energy while the vehicle is going downwards.

Such kinetic energy transformation into heat energy is responsible of brakes overheating, which provokes an excessive reduction of the vehicle braking capacity that might lead to accidents.

Therefore, one of the most common driving problems on steeped downgrades is the difficulty endured by heavy weight vehicles to control speed, without exceeding the service conditions of the braking system. In such a case the strengths resisting the movements are (Canale and Gutierrez, 2005): conventional engine braking system, rolling resistance strengths, aero-dynamical resistance strength and braking torque strength generated by auxiliary braking systems.

On one hand, the required braking power (HP_{req} , at hp) is the power generated by strengths enduring the movement in order to maintain a constant speed. It depends on downhill speed (V , at km/h); vehicle weight (W in tons) and; the slope inclination (i , in %), according to Equation 1 (DoT, 1981):

$$HP_{req} = \frac{WVi}{27,4} \quad (1)$$

2.2 Loss of braking capacity on downgrades

A vehicle's loss of braking capacity is caused by the reduction of friction coefficient between the covering cloth and the brake drum; or the brake pad and the brake disc due to overheating. Materials employed for the manufacture of covering clothes and brake pads shall slightly increase their friction coefficient when temperature is at the range of 150 to 250°C (Zanoli and Setti, 2004).

When an excessive overheating takes place (caused by the intensive and prolonged use of the servicing brake system on a steeped downgrade), it leads to brakes fading due to friction loss between the mechanical elements in the braking system. When the brake temperature returns to normal conditions, the friction level also becomes normal (Zanoli and Setti, 2004). According to Figure 1, the temperature provoking brake fading has not a fixed value, because it mainly depends on the braking system materials quality and the conditions provided at the moment the system is employed.

Figura 1. Resistencia al desvanecimiento del freno (Lucas y Widmer, 2004)

Figure 1. Resistance to brake fade (Lucas y Widmer, 2004)

However, it is possible to determine a range for limit temperatures based on the researches developed by different authors:

- Safe temperature for drum braking system at 216°C (DoT, 1981)
- temperatures exceeding 316°C, generally lead to brake fading (Limpert, 1999)
- drums brakes are sensitive to temperatures and they start losing efficiency when they reach temperatures higher than 250°C (Zanoli and Setti, 2004)
- in heavy weight vehicles owning drums braking systems, fading takes place as from 350°C (Lucas and Widmer, 2004)

Similarly, Lucas (2004) indicates that the use of better quality materials for the elaboration of covering clothes, pads, drums and discs, will increase braking capacity efficiency. Therefore, the fading limit temperature will be higher

3. The need of implementing arrestor beds

The loss of a vehicle control, while travelling on a downgrade, is caused by braking system fading. Fading is the consequence of overheating due to the excessive use of braking system, which purpose is to maintain the vehicle control on a steeped downgrade. In such a case, the implementation of arrestor beds is required, so that drivers are able to maintain the control of the truck, in spite of the braking failure and; to stop the vehicle safely. Naturally, the question of when to implement arrestor beds arises.

3.1 Regulatory Criteria

Design regulations provide a series of standards to response such a question. However, they are essentially reactive standards. Table 1 shows a summary of criteria recurrently employed by several design regulations.

Tabla 1. Criterios Normativos para definir la necesidad de emplazar lechos de frenado en pendientes descendentes prolongadas (Adaptado de Echaveguren et al., 2007; AUSTROADS, 2010 y AASHTO, 2011).

Table 1. Criteria for defining the need of arrestor beds in long downgrades (Adapted from Echaveguren et al., 2007; AUSTROADS, 2010 and AASHTO, 2011).

País /Country	Criterios / Criteria
Estados Unidos/ United States	En caminos existentes en donde los vehículos pesados tengan problemas operacionales/ Existing roads where heavy weight vehicles endure operational problems. En caminos existentes con evidencia de accidentes debido a corte de frenos/ Existing roads evidencing accidents due to braking systems failures. En caminos nuevos en donde se requieran pendientes descendentes prolongadas/ New roads on steeped downgrades.
Australia/ Australia	Pendientes entre 3 % en 8 km hasta 12 % en 1 km. $i > 38/L^{1.5}$ / Downgrades between 3 %, 8 km up to 12 %, 1 km. $i > 38/L^{1.5}$
Nueva Zelandia/ New Zeland	En caminos existentes con evidencia histórica de accidentes debido a corte de frenos/ Existing roads with accident historical records due to braking system failure.
Reino Unido/ United Kingdom	En caminos existentes con evidencia de accidentes debido a corte de frenos/ Existing roads evidencing accidents due to braking systems failures.
España/ Spain	En caminos nuevos en donde se requieran pendientes descendentes prolongadas/ New roads on steeped downgrades.
Sud África/ South Africa	En pendientes superiores al 5 % y cuando $CN > 60$ / Downgrades higher than 5 % and when $CN > 60$

Particularly, the Chilean Highway Manual (MOP, 2012) proposes the following considerations to justify the implementation of arrestor beds at some heavy traffic areas, which steeped slope is higher than 5%, besides meeting $CN > 60$. CN value is obtained by means of Eq. 2, where L is the length of the slope in km and; i is the longitudinal inclination expressed in %.

$$CN = i^2 L > 60 \quad (2)$$

The criteria proposed in Table 1 are wide and mostly of subjective nature, therefore, they are limited. Particularly, the criteria of Equation 2, as well as most criteria in Table 1, are easy to execute, but they do not allow us to correlate the genuine cause of the braking system failure, which is in fact the combination of heavy weight vehicles mechanical behavior, braking system, road geometry and driving performance. On the other hand, Abdelwahab and Morral (1997) proposed the use of the grade severity rating system created by Bowman (1989), but they did not implement it into a systematic design process.

3.2 Criteria based on the braking system temperature

Johnson et al. (1981) characterized the variables influencing the braking system fading. They determined that a braking system temperature mainly depends on the length and inclination of the slope, as well as the weight of the vehicle and its speed. On the other hand, it also depends on the ambient temperature, the initial temperature of braking system and the engine power, in accordance with researches by Limpert (1999) Karczewski (1992), Fitch (1994), Allen et al. (2000) among other authors.

Figure 2 shows the concept of Johnson et al. (1981). It depicts the temperature variation of brakes in service (T), in regards to the length percentage of path transited (L) for a vehicle entering the slope at a given speed. The driver shall maintain a constant speed until completing the downhill race.

To do so, the driver has to constantly employ the braking system, avoiding increasing the vehicle speed (increase caused by the vehicle weight and the slope inclination) during the whole downhill race.

Figura 2. Concepto de la temperatura límite (TL) del sistema de frenos

Figure 2. Concept of limit temperature (TL) of the brake system

Line 1 in Figure 2 shows the limit temperature (T_L) achievable by the braking system to meet optimal servicing conditions. By increasing braking system temperature (Line 2) and by reaching or exceeding T_L (Point A), brake fading takes place. Consequently, the overheating of brake system also takes place. In such a case, it is necessary to implement the arrestor bed, since there is a high probability of braking system failure on the downgrade. However, Line 3 shows a case where the braking power capacity is enough to avoid increasing braking system temperature by not exceeding limit temperature during downhill race. Consequently, the braking system failure is avoided.

4. Temperature profile of braking systems

The proposed method is based on the thermal balance condition of heavy weight vehicles' braking systems. According to Figure 2, when the temperature of a braking system reaches the limit temperature on a downgrade, the loss of friction in conventional braking systems takes place. In mathematical terms, above is expressed by Equation 3. This Equation shows that braking system temperature at the downhill end $T(L)$ is increased as long as the vehicle travels the downgrade. Such thermal variation may be expressed, according to Fitch (1994), as the addition of initial braking system (T_i) servicing temperature at the downgrade beginning, plus the incremental rise of braking system temperature.

$$T(L) = T(x) + \frac{dT(x)}{dx} \leq T_L \quad (3)$$

If the temperature of braking system is lower than the limit value (T_{LIM}) at all times, then the risk of braking system failure will be avoided. Otherwise, the brake system failure will occur, at some downhill point, and the implementation of the arrestor bed area will be required.

The temperature to the distance x is the result of the covered distance, vehicle mechanical characteristics and the slope longitudinal inclination. Therefore, the temperature varies as long as distance is increased, due to the vehicle weight and its downhill speed.

In practice, Equation 3 is employed to achieve the x point at the slope - where the braking system failure takes place - for the downgrade, length, downhill initial speed and vehicle weight. If the x point is achieved within the L downgrade length, then the implementation of the arrestor bed area is required. Otherwise, it is not required.

A relevant aspect to be considered is that this conceptual approach enables the determination of the Maximum Safety Downhill Speed (VMDS), which is the maximum allowed speed for heavy weight vehicles driving downwards to avoid brake systems failures. Such value shall be indicated by a sign post at the downgrade entrance.

Returning to Equation, the brake system temperature - at any point on the slope - is calculated by using Equation 4 by Bowman (1989).

$$T(x) = T_i + \left[T_\infty - T_i + \frac{K_2 HP_B - 32}{1,8} \right] (1 - e^{-K_1 x/V}) \quad (4)$$

Where T_i is the braking system temperature at the downhill beginning ($^{\circ}\text{C}$); T_∞ is the ambient temperature ($^{\circ}\text{C}$); x is the downgrade length from its beginning point (km); HP_B is the power produced by servicing brake system (hp) and; V is the circulation speed (km/h). Constants K_1 (in $1/h$) and K_2 (in $^{\circ}\text{F}/hp$) were calibrated for conventional trucks. According to Fitch (1994) they are calculated as follows:

$$K_1 = 1,23 + 0,016V \quad (5)$$

$$K_2 = \frac{1}{0,10 + 0,0013V} \quad (6)$$

Braking power capacity depends on the gross power required to stop a vehicle (HP_{req}), on the power consumption per tread layer (HP_{tread}), engine power consumption (HP_{engine}) and braking power of auxiliary braking systems ($K_{aux} HP_{aux}$).

$$HP_B = HP_{req} - HP_{rodado} - HP_{motor} - K_{aux} HP_{aux} \quad (7)$$

Therefore, the braking power capacity is determined by using Equation 8.

$$HP_B = \frac{WVi}{27,4} - \frac{WVR_C}{27,4} - HP_{motor} - K_{aux} HP_{aux} \quad (8)$$

Where W is the vehicle total gross weight, expressed in tons; V is the speed at downhill entrance, in km/h; i is the longitudinal downgrade, in %; RC is the tread layer coefficient, which depends on the traffic circulation speed.

The constant K_{aux} corresponds to the factor determining the braking power amplifier effect, due to the use of auxiliary braking systems, such as engine brakes, exhaust brakes and brake retardant systems. Such systems notably increase braking capacity and they work together with brake conventional systems (Brossi, 2002; Widmer, 2000). Meanwhile, temperature differential is calculated by means of Equation 9, which assumes by default that temperature variation is constant.

$$\frac{dT(x)}{dx} = 1,5 \times 10^{-4} WV^2 - 17,8 \quad (9)$$

5. Criteria formulation for arrestor beds

This section needs presents a solution set for downgrades, length and entrance speed that justifies the implementation of arrestor beds for conventional 45-ton-heavy weight vehicles and for high tonnage configuration of 61 and 75 tons. The latter correspond to high tonnage configurations (CAT), which are available in some Latin-American countries only, mainly due to design and logistics operational regulations (Diaz et al., 2012). First of all, the characterization of each heavy vehicle configuration is presented. Afterwards, the geometrical conditions employed for this model are also introduced. Finally, the applications of equations 3 up to 9 are simulated.

5.1 Load Configurations for Heavy Weight Vehicles

Configurations for loading and braking systems are indicated in the Table 2. Combinations were selected in accordance with CAT proposed by Diaz et al. (2012), taking into account its potential utilization in Latin-America.

Tabla 2. Configuraciones de vehículos pesados para la modelación**Table 2.** Heavy vehicle configurations for modeling

	Configuración de carga / <i>Load configuration</i>	Potencia máxima del motor (hp) / <i>Maximum engine power (hp)</i>	Potencia de frenado (hp) / <i>Brake power (hp)</i>
C1	Tracto + semirremolque: 45 T / <i>Articulated truck : 45 T</i>	360	Freno de escape: 216 / <i>Exhaust brake: 216</i>
C2	Bitrén corto de 7 ejes: 61 T / <i>Short heavy load truck of 7 axles: 61 T</i>	360	Freno de escape: 216 / <i>Exhaust brake: 216</i>
C3	Bitrén largo de 9 ejes: 75 T / <i>Long heavy load truck of 9 axles: 75 T</i>	360	Freno de escape: 216 / <i>Exhaust brake: 216</i>
C4	Bitrén corto de 7 ejes: 61 T / <i>Short heavy load truck of 7 axles: 61 T</i>	400	Retardador hidráulico: 560 / <i>Hydraulic retarder: 560</i>
C5	Bitrén largo de 9 ejes: 75 T / <i>Long heavy load truck of 9 axles: 75 T</i>	400	Retardador hidráulico: 560 / <i>Hydraulic retarder: 560</i>

5.2 Geometrical Configurations used for the analysis

The ranges of geometrical variables making up the assessment scenarios considered downgrade length, inclination and incoming speed at the slope.

- Downgrade length: from 1 to 12 km.
- Downgrade inclination: slopes at 4%, 6%, 8% and 10% were included.
- Circulation speed: a circulation speed at the downgrade entrance point was considered, then reaching the maximum speed limit, which is 120 km/h in Chile.

5.3 Calculation for the Implementation Criterion

In accordance with above results, it becomes convenient to update the criterion actually in force. For this purpose a conventional truck of 45-tons total gross weight was considered. This value represents the most recurrent limit weight accepted by the regulations for maximum allowed weight in different countries. This truck corresponds to load configuration C1.

By considering above, the need of implementing the arrestor bed may be determined based on two criteria. One: related with the CN value (Ref, Equation 2) without entrance limit speed restrictions but the legal speed limit. The other one is based on a dangerousness index, which in turn also depends on the relation between downgrade operation speed and the VMDS.

For new roads, the first criterion allows to design steeped downgrades to avoid the implementation of the arrestor bed, or to design where to place it instead. The second criterion allows the implementation of maximum speed limit sign posts, at the downgrade entrance on new roads. For existing roads, the second criterion may establish a rule to determine the dangerousness levels of slopes according to operation conditions.

Criterion 1: CN value without speed restrictions

This criterion was developed for load configuration C1 (Table 2). By using such data, multiple combinations of downgrade inclinations and lengths were assessed,

on the condition that the VMDS speed would be equal to the traffic circulation speed at the downgrade beginning point, thus guaranteeing that a brake system failure would not take place. In this way, the critical values for downgrade and downhill length were already available. Afterwards, the CN value was calculated for each inclination and length combinations, by using the Equation 2, in function of the incoming speed; thus achieving the results shown by Table 3.

Tabla 3. Criterio propuesto para justificar un lecho de frenado

Table 3. Suggested approach to justify an arrestor bed

Velocidad de entrada (km/h)/ Entrance speed (km/h)	CN	Velocidad de entrada (km/h)/ Incoming speed (km/h)	CN
30	> 560	80	> 210
40	> 410	90	> 170
50	> 340	100	> 140
60	> 290	110	> 110
70	> 250	120	> 90

This criterion considers the incoming speed and loaded truck weight, therefore, the value is less restrictive than the currently employed CN value (CN = 60). Consequently, it is now possible to determine the arrestor bed implementation for conventional braking system trucks, based on the initial operation speed and total gross weight. For instance, at an incoming speed of 60 km/h, the arrestor bed is required when CN > 290, which limits the election of the variables downgrade and downhill length. For example, downgrades of 7 % up to 5.9 km and 8 % up to 4.5 km meet this criterion.

Criterion 2: Dangerousness Index

So as to determine this index, the concepts from the reliability theory were applied, by assuming given normal distributions for traffic circulation speed and VMDS, as well as failure function linearity. These theoretical assumptions enable us to use Equation 10 to calculate the reliability index (Echaveguren et al., 2005).

$$\beta = \frac{\mu_{V_{op}} - \mu_{VMDS}}{\sqrt{\sigma_{V_{op}}^2 + \sigma_{VMDS}^2}} \quad (10)$$

The numerator in Equation 10 represents the difference between the mean distribution probabilities for the operation downgrade incoming speed (V_{op}) and the VMDS. The denominator represents the standard deviation for both speeds. As long as V_{op} is greater than VMDS, the failure probability is also greater. If V_{op} is equal or lower than VMDS, failure probability is zero.

Operation speed may be directly obtained from measurements at the road site. Therefore, the speed standard deviation can be estimated at 4 km/h, in accordance with the authors' experience, in case site data are not available. VMDS standard deviation may be determined for each geometrical configuration. By simulating load configurations in Table 2, all possible combinations of inclination and downgrade lengths were obtained. By employing the Equation 3 to Equation 9, the expression of Equation 11 was achieved, which represents the failure envelope for VMDS based on the parameter CN in Equation 2.

$$VMDS = \begin{cases} V_L & ; VMDS \geq V_L \\ 120 \left[1,04 - 0,9e^{-\frac{47.489,2}{CN^2}} \right] & ; VMDS < V_L \end{cases} \quad (11)$$

Simulations conducted by employing the Equation 11 provided a maximum standard deviation estimated at 3 km/h. Furthermore, by considering end-to-end β values, the dangerousness index (IP) in Equation 12 was elaborated, which represents the occurrence probability of braking system failure based on the road geometry, heavy weight vehicles operation and loading conditions. Above in function of the average for the operation speed and VMDS obtained by employing Equation 11.

$$IP = \begin{cases} \frac{(\mu_{V_{op}} - \mu_{VMDS})/3,6}{27,7} 100 & ; \mu_{V_{op}} > \mu_{VMDS} \\ 0 & ; \mu_{V_{op}} \leq \mu_{VMDS} \end{cases} \quad (12)$$

This index enables an easy calculation on downgrades dangerousness conditions. For example, a downgrade of 8% in 5 km, $CN = 320$. According to Equation 11, $VMDS = 57$ km/h. If the operation speed is 120 km/h, the index in Eq. 12 is $IP = 63,3\%$. If the operation speed is 100 km/h, $IP = 43,2\%$. For operation speed at 80 km/h $IP = 23,2\%$ and at 60 km/h $IP = 3,1\%$. These results prove that the greater difference between operation speed and VMDS, the greater failure probability is. Therefore, if data from road geometrical and heavy weight vehicles operation conditions are available, then it will be possible to determine the grade dangerousness ranking for existing roads, by using only one system.

6. Studying a case for special load configurations

This category includes vehicles load configurations C2 to C5 in Table 2. Such configurations allow maximum gross tonnages from 45 to 75 tons. The vehicles have auxiliary braking systems of greater power capacity than conventional loading vehicles. Although such vehicles are not available in several countries of this region, it is interesting and convenient to analyze the potential effect of such configurations on the criteria employed to evaluate the need of implementing arrestor beds.

Figures 3a, 3b, 3c, and 3d show the criteria for implementing arrestor beds for load configurations C2, C3, C4 and C5 based on the downgrade geometry and the incoming operation speed on the slope. The graph also provides the criterion employed by Chilean regulations (CN = 60), so as to show the existing differences considered when evaluating the vehicle weight and its braking system behavior.

In the abacus of Figures 3a, 3b, 3c and 3d, the curve is chosen in function of the operation speed at the downgrade entrance point. Afterwards, by using the downgrade length and inclination, the coordinate point is located on the graph. If the point is located at the curve left side, then the VMDS is lower than the operation speed at the downgrade entrance point, therefore it will be necessary to implement the arrestor bed. Contrarily, if the point is located at the curve right side, the arrestor bed is not required at all.

So as to exemplify above, a downgrade with an inclination of $\theta = 6\%$ and downgrade length of 5 km was considered. The circulation speed used to determine the potential implementation of the arrestor bed was assumed as $V_{op} = 70$ km/h. Each graph shows the coordinate point for the selected geometrical configuration.

Figura 3a. Criterio CN. Configuración C2
Figure 3a. Criterion CN. Configuration C2

Figura 3b. Criterio CN. Configuración C3
Figure 3b. Criterion CN. Configuration C3

Figura 3c. Criterio CN. Configuración C4
Figure 3c. Criterion CN. Configuration C4

Figura 3d. Criterio CN. Configuración C5
Figure 3d. Criterion CN. Configuration C5

In accordance with Figure 2, it is observed that for configurations C2, C3 and C5 with auxiliary braking systems, the coordinate point is located at the curve left side, at 70 km/h; therefore the implementation of the arrestor bed is justified. Only configuration C4, with braking retarders does not require the arrestor bed. Braking retarders for medium and high weight vehicles (61 tons) are able to maintain the constant downhill speed. For the other cases, the braking system is not able by itself to maintain downhill speed and temperature. Consequently, there is a braking failure probability.

It is also observed from Figure 3 that in all cases, that the curve describing the criterion $CN = 60$ is located below the proposed curves, thus turning it into a very conservative criterion. Therefore, the implementation of the arrestor bed is required by downgrade inclinations and lengths combinations which are lower than the proposed criterion.

7. Conclusions

It was concluded that criteria proposed by regulations based on geometrical indexes are not aware on the mechanical performance of heavy weight vehicles. Therefore, they tend to recommend the implementation of arrestor beds in cases they are not required.

The method approach in this research job combines the information on downgrades geometrical design and the mechanical performance of heavy weight vehicles travelling down these slopes. The approach provides designers with supporting tools to modify downgrade geometry, to place maximum downhill speed sign posts and determine the downgrades dangerousness indexes leading to design the bed arrestor implementation.

Since the operation speed at the downgrade entrance point is different to the downhill speed, the criterion based on CN is essentially a design criterion to be used for new roads, where the traffic circulation speed is not available yet. In this case the VMDS calculation may be used to determine a limit speed at the downgrade entrance point, by assuming that this speed will be constant alongside the slope and, provided that service braking systems of heavy weight vehicles will be used.

The increase of heavy vehicles total gross weight, over 45 tons, without improving the engine power and braking systems available for conventional trucks, has a significant impact on the implementation of arrestor beds at downgrades. This research proved that all load configurations for 61 and 75 tons vehicles require arrestor beds, at traffic circulation speeds lower in 50 to 70% compared to conventional trucks.

The use of reliability concepts to determine failure probability enables the incorporation of the operation speed variability and the maximum downhill speed variability. This variability may be represented by means of a failure function, which in turn allows the determination of downgrades dangerousness levels. Therefore, these concepts provide an objective point of view for the design and analysis of existing roads safety conditions.

Furthermore, the maximum downhill speed may be conveniently used to standardize the operation speed at the downgrade entrance point by using sign posts. However, some elements placed prior to the downgrade entrance point, such as emergency escape lanes used for braking systems inspection, are only complementary solutions to the implementation of arrestor beds.

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