AUXILLARY BRAKING. A PERFORMANCE BASED STANDARD PROPOSAL

S. SAAVEDRA

National Polytechnic Institute (IPN). Mechanical and Electrical Engineering College (ESIME).
Graduate of Mechanical Engineering; Master in Management.
Currently representative of the National Chamber of Transformation Industries (CANACINTRA) for negotiating Transport and Vehicle Regulations.
President of the Automotive Industry Sector at the National Chamber of Transformation Industries (CANACINTRA)
Active member and cofounder of the National Alliance for Road Safety (ANASEVI)
Active member and cofounder of the Technology and Maintenance Council in Mexico (CMT)
Partner and Technical Director at Entorno Industrial, S.A. de C.V.
CEO Tecnología para el Transporte SALS, S.A. de C.V.

Abstract

This paper presents a regulatory solution to a safety problem of heavy vehicles in Mexico. The demography and topography of the country present several challenges, considering that almost 30% of the population live in cities at an altitude above 1900 m above sea level, with hills between cities topping 3000 m, therefore supplies for everyday use as well as those for the industry need to be either brought up or send down to or from the rest of the country. Current regulation requires that vehicles with a GVW greater than 7,257 kg be equipped with an auxiliary braking system. Many of the downhill road sections limit the speed of heavy vehicles to 60 km/h, thus such speed has been selected for the proposed PBS on roads classified as ET and A. The standard, when in place, will limit the configuration a truck tractor can be part of, as well as the downhill road sections where it can travel with such configurations. A discussion on the various problems that should be overcome to implement the PBS is presented.

Keywords: High-Capacity Transport, Double Trailer Configurations, Weight and dimensions regulation in Mexico, Auxiliary braking, Performance based standard.

Contents.

1. Introduction

The demography and topography of the country present several challenges, considering that almost 30% of the population leave in cities at an altitude higher than 1900 m above sea level, with hills between cities topping 3000 m, therefore supplies for everyday use as well as those for the industry need to be either brought up or send down to or from the rest of the country. Some of the downhill road sections have a height differential of close to 1,000 m in a length of 19 km, while others have downhill grades up to 6.5% in a length of 5 km, with toll collection areas at the end of the downhill road section. Around 80% of the goods are transported by road using the approved vehicle configurations allowed by the weights and dimensions regulation NOM-012-SCT-2-2017[1], including double trailer configurations with a GVW as high as 75.5 metric tons. The regulation requires that vehicles with a GVW greater than 7,257 kg be equipped with an auxiliary braking system, however the said regulation does not indicate the specification of those auxiliary braking systems, nor the performance expected from the vehicle when driving downhill; the regulation only defines auxiliary braking as all those devices which reduce the speed of a vehicle without the use of friction material contacting a metallic surface, such as engine brakes, exhaust brakes, retarders, either electro-magnetic or hydraulic, or any other.

2. Downhill road conditions of various roads in Mexico.

Some road sections with the most transit of heavy vehicles with a steep and long downhill road section, where collisions due to brake failure occur are shown in Table 1. The table identifies the “name” of the road section, the initial and final altitudes above sea level (ASLi and ASLf), de difference in ASL for the analyzed road section, the distance to travel between

[1] NORMA Oficial Mexicana NOM-012-SCT-2-2017, Sobre el peso y dimensiones máximas con los que pueden circular los vehículos de autotransporte que transitan en las vías generales de comunicación de jurisdicción federal.

the initial and final ASL ad finally de calculated average slope between both referenced points.

Two road sections are highlighted as they have the greatest difference in altitude, also as they report the most incidents of brake failures, the most usage of emergency ramps, and in the case of PUE -CDMX LLano largo to San Marcos Toll several crashes of heavy vehicles with toll booths and vehicles in the line have occurred. In the case of these two roads some subsections are included to show that they have a steeper slope then the average of the road section.

ROAD SECTION	ASLi	ASLf	DOWNHILL (m)	DISTANCE (km)	SLOPE
La venta - Sam´s Santa Fe	2853	2641	212	4.94	4.29%
La Venta - Puerta Santa Fe	2853	2487	366	8.15	4.49%
TOL-CDMX Las Cruces – toll booth	3151	2861	290	6.34	4.57%
CHAMAPA Caseta - puente Interlomas	2782	2466	316	6.91	4.57%
PUE - CDMX First emergency ramp to second emergency ramp	3010	2841	169	3.12	5.42%
PUE -CDMX LLano largo to San Marcos Toll	3200	2251	949	22.03	4.31%
Conin - Querétaro	2037	1873	164	4.70	3.49%
CDMX - TOL La Marquesa to Toll	3008	2764	244	4.25	5.74%
Esperanza – second emergency ramp	2432	1975	457	9.44	4.84%
Esperanza - Cd Mendoza straight	2432	1530	902	19.87	4.54%
Carr 57 Toll Road start to Arteaga Toll	2173	1782	391	9.56	4.09%
Huizilac to OXXO	2440	2160	280	2.58	10.85%

Table 1. Some Road Sections with critical slope.

In figures 1 and 2, taken from Google Earth[2], the path of the road section Esperanza - Cd Mendoza straight is clearly seen. This a divided highway with two lanes on each direction. The direction going downhill is much shorter than the direction going uphill being 19.87 km vs 28.65 km, so the resulting slopes are 4.54% vs 3.15%. The oldest part of the highway is the longest, being built in the early 1960s; the newest part was put in service in the 1990s. Fog is a common situation on this highway as it faces the clouds coming to the hillsides from the Gulf of Mexico. Even though the maximum speeds recommended for heavy vehicles should not exceed 60 km/h on this road section, there are several signs indicating a maximum speed of 80 km/h.

[2] 2022 Google LLC. All rights reserved.

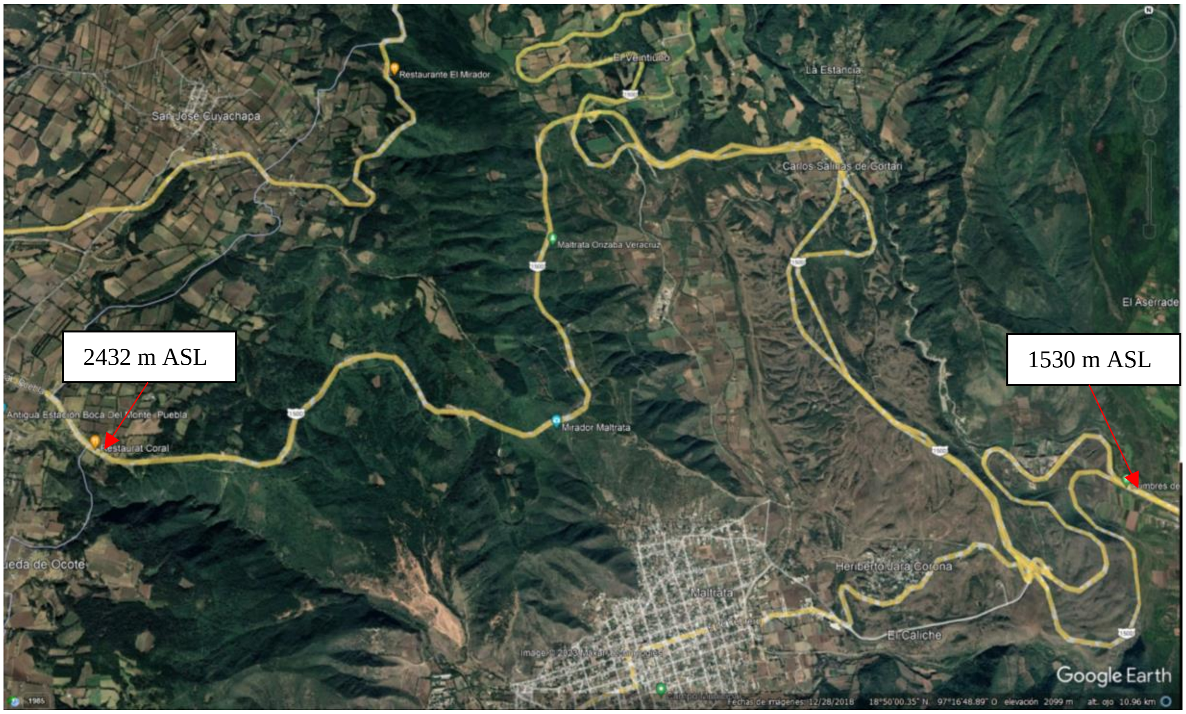

Figure 1. Aerial view of the path of the road section Esperanza - Cd Mendoza straight.

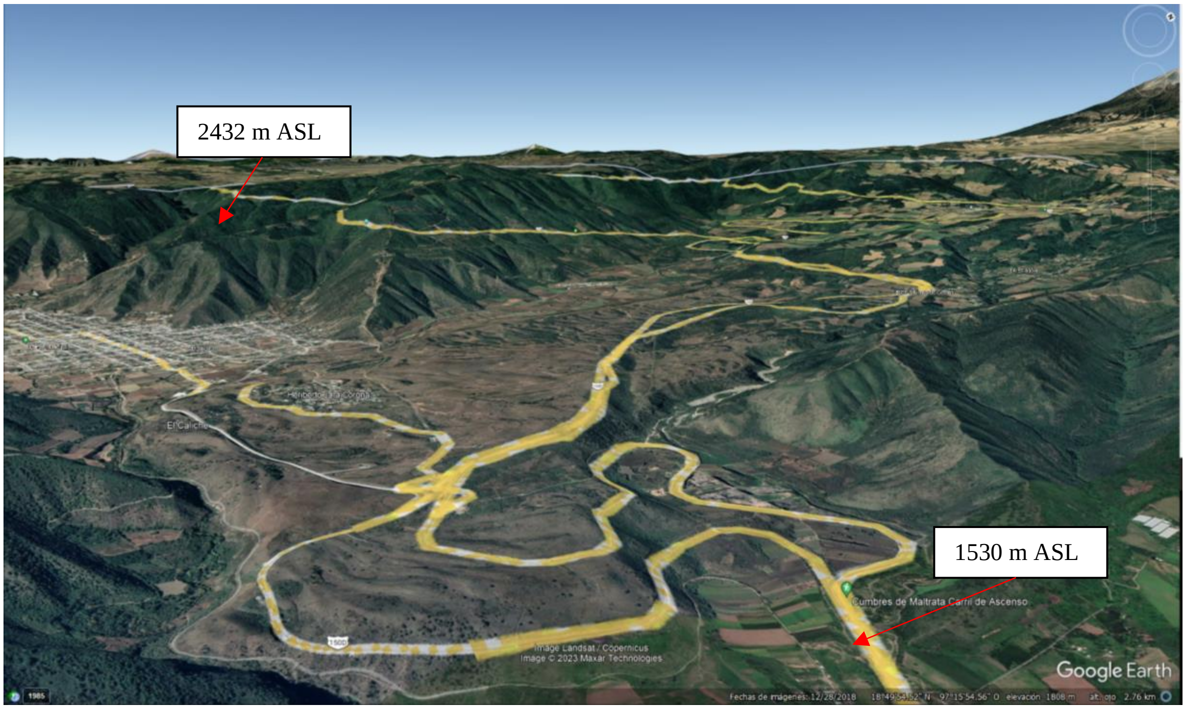

Figure 2. Side view of the path of the road section Esperanza - Cd Mendoza straight.

3. Vehicle configurations allowed in Mexico.

The NOM-012-SCT-2-2017[3] includes 28 different vehicle configurations, 4 for buses (B), 3 for unit trucks (C), 4 for trucks with trailer (C-R), 6 for truck tractor with semitrailer (T-S), 8 for truck tractor with semitrailer and full trailer (T-S-R) and 3 for truck tractor with two semitrailer (T-S-S), which means 4 vehicle configurations for passenger vehicles and 24 for cargo vehicles. Of those 24 cargo configurations 3 are the most used on the highways, the unit truck with 3 axles (C3), the 3 axle truck tractor with the 2 axle semitrailer (T3-S2) and the 3 axle truck tractor with 2 axle semitrailer and 4 axle full trailer (T3-S2-R4). The maximum allowed length and weight of these configurations are shown in Table 2.

NAME OF CONFIGURATION	MAX LENGTH (m)	MAX GVW (kg)
Unit truck with 3 axles (C3)	14.0	27 500
3 axle truck tractor with the 2 axle semitrailer (T3-S2)	23.0	46 500
3 axle truck tractor with 2 axle semitrailer and 4 axle full trailer (T3-S2-R4)	31.0	75 500

Table 2. Most typical cargo vehicle configurations.

Needless to say that it is not uncommon that some transportation companies overload their vehicles and thus transit with a GVW heavier than that allowed by the regulation. This situation poses a threat to safety and road conservation, as it becomes more complicated to drive downhill.

4. Energy considerations of the vehicles driving downhill.

Any moving vehicle has a kinetic energy (Ec) at any given time equals to the square of its speed times half of its mass. When a vehicle is about to transit a downhill road, it also has a potential energy (Ep) equals to its mass times the height of the downhill times g.

In an ideal world where no losses of energy due to friction, aerodynamics or other external factors exist, all potential energy of the vehicle at the top of the hill may transform in kinetic energy at the end of the downhill. How fast would a vehicle be at the end of the Esperanza - Cd Mendoza straight road section if it is traveling at a speed of 50 km/h at the top of the hill and nothing prevents it from gaining speed?

$$Ec = \frac{1}{2} m \times v^2 \qquad = \qquad Ep = m \times g \times h$$

$$\frac{1}{2} m \times v^2 = m \times g \times h$$

$$v = \sqrt[2]{2 \times g \times h} = \sqrt{2 \times 9.81 \times 902} = 133\, m/s = 479\ km/h$$

[3] NORMA Oficial Mexicana NOM-012-SCT-2-2017, Sobre el peso y dimensiones máximas con los que pueden circular los vehículos de autotransporte que transitan en las vías generales de comunicación de jurisdicción federal.

Final speed = 50 km/h + v = 529 km/h

Another way to look at the energy issues of a vehicle traveling on these long downhills is comparing the amount of potential energy against known issues.

Let's compare the kinetic energy to be dissipated during a panic braking of the heaviest allowed configuration traveling at a speed of 80 km/hr:

$$Ec = \frac{1}{2} m \times v^2 \; = \frac{1}{2} \times 75500 \times 22.22^2 = 18\ 638\ 247\ J$$

With the potential energy of the same vehicle configuration at the top of the Esperanza - Cd Mendoza straight road section:

$$Ep = m \times g \times h = 75500 \times 9.81 \times 902 = 668\ 070\ 810\ J$$

So

$$Ep \div Ec = 35.8$$

In simple words the potential energy of the vehicle before starting its travel downhill is equivalent to the energy to be dissipated if the vehicle traveling at a speed of 80 km/h experiences 35 panic braking situations each one every 25 seconds. There is no way that friction based braking systems may withstand such an amount of energy without reaching a temperature that will cause the brake system to fail. It will fail well in advance of the 35th brake application.

5. Existing formulae to determine the capacity of auxiliary brakes.

I found that the Technology and Maintenance Council of the American Trucking Associations in their Recommended Practice RP636-1[4] includes a formula that can be used to determine the horsepower (HP) that must be absorbed by the vehicle in order to maintain a given speed (MPH), when traveling downhill with a percent of grade (PG), with a gross vehicle weight (GVW). The formula is in imperial units as follows:

$$HP = 0.002667 \times GVW \times MPH \times (\sin\left(\arctan\left(\frac{PG}{100}\right)\right))$$

This recommended practice proposes to equip the vehicles with an auxiliary braking system when the natural retardation force of the vehicle is not enough to keep the vehicle speed when traveling on mountain downgrades. The conditions considered to provide natural retardation force to the vehicle are the engine size (considering that most of the engines in the USA are

[4] RP636-1 Specifying auxiliary retarders issued on 3/98 TMC/ATA.

equipped with engine brake system), axle and transmission gearing, aerodynamic treatments, tire type, etc. All of them impact the horsepower that the vehicle absorbs on its own.

I found necessary to have a formula based on general units of measure, as well as easy for the transportation company to understand and use. Though I find it correct to use the expression "$\sin\left(\arctan\left(\frac{PG}{100}\right)\right)$" in the formula, it is my opinion that it will be complicated to understand and use for the transportation companies, so in my proposal I include the percent grade in % directly in the proposed formula, for percent grades that are not steeper than 12% considering that:

$$\sin\left(\arctan\left(\frac{12}{100}\right)\right) = 0.1191; \sin\left(\arctan\left(\frac{10}{100}\right)\right) = 0.0995; \sin\left(\arctan\left(\frac{5}{100}\right)\right) = 0.0499$$

So, in the case of 10% grade the variation of the calculated power would vary by less than 0.5%. The proposed formula to be used in the PBS would be as follows:

$$kW = 2.725 \times GVW \times v \times PG$$

Where:

kW = Power of the auxiliary braking system
GVW = Mass of the vehicle configuration in thousands of kilograms
v = Speed of the vehicle while traveling downhill in km/h
PG = Percent grade of the road in %

6. Aerodynamic drag and rolling resistance considerations.

Taking into consideration that the maximum vehicle speed considered under this PBS is 60 km/h, I proceed to analyze the impact of aerodynamic drag and rolling resistance in reducing or limiting the speed of the vehicle when traveling downhill. The analysis is done with two double trailer configurations with the heaviest weight allowed, one with high dry van trailers and the other one with low height cargo on flatbeds.

6.1 Aerodynamic drag.

Truck and trailer designs have seen significant improvements in the last decade in terms of aerodynamics. In North America environmental regulations have imposed the use of aerodynamic devices to reduce fuel consumption and thus emissions. These improvements result in lower forces opposing to movement when traveling downhill and thus requiring more power from the auxiliary braking system.

Drag force (F_d) depends on the half of the density of air (ρ), so the highest the altitude the lower the density of air, the drag coefficient (c_d), so the most aerodynamic design of the configuration, the lower this coefficient, the frontal area of the configuration (A), so the smaller the area the lower the drag force, and the square of the configuration speed (v), so the higher the speed the much higher the drag force opposing the movement. Following the formula to determine the drag force:

$$F_d = c_d \times 0.5\rho \times v^2 \times A$$

Varios studies show drag coefficients for tractor trailer configurations in the range of 0.6 to 0.9, so for our analysis we will use 0.6 for c_d.

Truck trailer configurations are allowed a maximum width of 2.6 meters. Typica height of a dry van is 4.20 m, while a low height loaded flatbed is not higher than 2.3 meters, so in this case the height to be considered is a low roof tractor with a height of 2.9 meters.

Considering the altitude of most of the roads that would require the use of auxiliary braking systems, the specific gravity of air is considered to be 1 kg/m^3.

The calculated drag force for the double trailer configuration at the maximum weight with dry van trailers and with low height flatbed traveling at 60 km/h is shown in Table 3:

NAME OF CONFIGURATION	DRAG FORCE
3 axle truck tractor with 2 axle semitrailer and 4 axle full trailer (T3-S2-R4) with dry vans	910 N
3 axle truck tractor with 2 axle semitrailer and 4 axle full trailer (T3-S2-R4) with low height loaded flatbeds	628 N

Table 3. Drag forces at 60 km/h.

6.2 Rolling resistance.

Rolling resistance is defined as the force that resists the motion of a body rolling on a surface. It can be expressed by the following generic formula:

$$F_r = c \times W$$

Where:

F_r = rolling resistance
c = rolling resistance coefficient
W = weight of the vehicle normal to the rolling surface = m*g
m = mass of the body
g = 9.81 m/s^2

The calculated rolling resistance of our double trailer configuration when traveling on a 5% downgrade hill is shown in table 4.

NAME OF CONFIGURATION	ROLLING RESISTANCE FORCE
3 axle truck tractor with 2 axle semitrailer and 4 axle full trailer (T3-S2-R4)	4,222 N

Table 4. Rolling resistance force

6.3 Figure 3 shows the forces acting on the vehicle configuration. In our example for the analysis our vehicle configuration with a mass of 75,500 kg traveling on a 5% gradient requires a braking power of 826 HP to maintain a speed of 60 km/h.

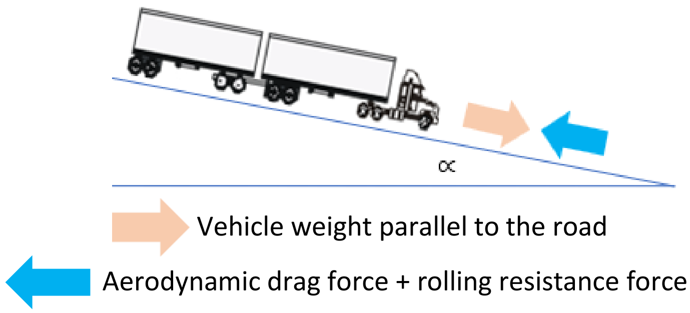

Figure 3. Opposing forces when traveling downhill

The total calculated forces that oppose to the movement of the vehicle configuration with dry van trailers are the aerodynamic drag force (F_d) + rolling resistance (F_r), and may be expressed in term of power considering the speed of travel of the vehicle as follows:

$$HP = (F_d + F_r) \times v \times 1.341 = (910 + 4222) \times \frac{60}{3.6} \times 1.341 = 114.7\, HP$$

So the power of the forces that oppose to the movement is around 14% of the power needed to keep the speed of the dry van configuration and 13% of the low height flatbed configuration.

6.4. Based on the above calculations the theoretical formula for auxiliary braking power may be expressed as follows:

$$kW = 2.725 \times GVW \times v \times PG \times 0.87$$

7. Are auxiliary braking systems needed in the Mexican highways?

When the NOM-012-SCT-2-2008 was released, it included various requirements for the vehicle configurations to be allowed with an additional weight. Many of those requirements were related to vehicle safety and a couple of them were related to the weight itself. The current NOM-012-SCT-2-2017 made those requirements mandatory for the double trailer configurations. One of the requirements is the minimum HP required, which is related to the maximum GVW allowed. In the case of the three most common vehicle configuration the requirements are shown in Table 3.

NAME OF CONFIGURATION	HP min	MAX GVW (kg)
Unit truck with 3 axles (C3)	215	27 500
3 axle truck tractor with the 2 axle semitrailer (T3-S2)	350	46 500

NAME OF CONFIGURATION	HP min	MAX GVW (kg)
3 axle truck tractor with 2 axle semitrailer and 4 axle full trailer (T3-S2-R4)	450	75 500

Table 5. HP required for the most typical cargo vehicle configurations.

Typically the engine brake provides a brake power of between 40% and 60% of the engine power, depending on the rpms of the engine, and it can not be used for long periods of time as it may over heat the engine. For calculation in the table below I will use 50%.

In order to verify if said configurations have enough power to keep the vehicle at a speed of 60 km/h when traveling on the Esperanza - Cd Mendoza straight road section (4.54% PG), I proceed to use the formula above and convert the results to HP using a conversion factor of 1 kW = 1.341 HP. The results are shown in table 4. In the last column I am deducting the power resulting from the aerodynamic drag force (AD) plus the rolling resistance (RR) of a low height load flatbed configuration.

NAME OF CONFIGURATION	Engine brake HP	Calculated auxiliary braking HP	Calculated AB HP including AD and RR
Unit truck with 3 axles (C3)	107	273	238
3 axle truck tractor with the 2 axle semitrailer (T3-S2)	175	540	470
3 axle truck tractor with 2 axle semitrailer and 4 axle full trailer (T3-S2-R4)	225	752	654

Table 6. Braking HP comparison for the most typical cargo vehicle configurations

It is notorious that these vehicle configurations should not travel at a speed of 60 km/h on this road section when loaded to the maximum allowed GVW, as they do not have enough braking power to maintain the speed, unless they are equipped with an auxiliary braking system.

Calculated braking power using the formula of section 5 may be decreased by 13% for low height flatbed configurations or 14% for dry van type configurations. Other percentages may be used when practical tests are run to determine the natural retardation power of the vehicle configurations.

The other factor in selecting the auxiliary braking systems is the amount of energy that the system must dissipate during the downhill travel. Friction brakes have enough power to stop a vehicle, but they do have a limited capacity to dissipate the heat. If calculations indicate that, in order to maintain the speed on a downhill road, it is needed to apply a panic braking at cycles of every 3 minutes or less, more than 5 times, then an auxiliary braking system is needed for safe travel.

8. Proposal of performance-based standard (PBS).

8.1 Auxiliary braking

8.1.1 Purpose and intent

a) Purpose

The primary purpose of this standard is to manage the safety risk associated with the loss of service brake power due to overheating when traveling downhill.

b) Intent

When traveling downhill vehicles tend to gain speed by the conversion of potential energy into kinetic energy. In order to reduce the speed, drivers may apply the service brakes and/or use the engine brake. Service brakes usually have great braking power but may fade as temperature increases, or the heat generated may ignite the tires of the vehicle. Engine brake have limited power and can not be used for prolonged periods of time as the engine may get too hot. An auxiliary braking system independent of the service brakes with enough braking power and the ability to dissipate the heat generated without affecting other vehicle components is needed during steep and long road sections.

8.1.2 Definition

a) Summary statement

The ability to maintain the speed of a vehicle when traveling downhill without applying the service brakes.

b) Detailed statement

When operating at maximum laden mass, a vehicle configuration participating in the scheme must be able to maintain steady forward motion speed on a road section with the specified downgrade during still air conditions.

8.1.3 Measure

a) Performance value

The auxiliary braking system must be able to sustain a steady speed of the vehicle without applying the service brakes. The speed must be measured and recorded at the achieved performance value, in units of km/h rounded down to the nearest whole value.

b) Performance levels

Road classification	**Downgrade**	**Length of road section (min)**	**Performance level required**
ET and A	5%	10 km	60 km/h
B	6%	6 km	50 km/h
C and D	8%	4 km	40 km/h

Table 7. Maintain speed performance levels.

8.1.4 Test specification

a) Test load

The vehicle being assessed must be loaded to its maximum laden mass. Each tire on the vehicle must have a tread depth of at least 90% of the original value over the whole tread width and circumference of the tire. Each tire must be inflated to the pressure as specified by the vehicle and/or tire manufacturer.

b) Test conditions

The full length of the vehicle being assessed must be on a downgrade. The test site must have uniform, smooth, dry, hard pavement, which is free from contaminants. The surface must have a coefficient of friction value, μ_{peak}, at the tire/road contact surface of not more than 0.80. Weather conditions should be clear skies, with still air or wind velocity not grater than 10 km/h.

c) Test procedure

With the vehicle being assessed in forward motion on a slope having a downgrade as specified in Table 7, steady forward motion must be maintained at a speed not greater than the specified speed for the entire length of the road section. Steady forward motion is when the forward speed of the vehicle on the downgrade is either constant or decreasing for a period of at least 5 seconds.

D) Test method

Numerical modelling (computer-based simulation) including braking power requirements less aerodynamic drag and rolling resistance or field-testing.

8.1.5 Identification

Vehicles (trucks and truck tractors) are identified with a tag indicating the maximum mass allowed to travel on downhill road sections.

9. Implementation recommendations.

The process to implement a PBS standard as the one presented in this paper requires several previous steps as follows.

9.1 The PBS system.

There is no experience with the PBS system in Mexico. There is experience with prescriptive regulations only. So an education process with all stake holders should be carried out before launching any PBS standard. It may be required to update the Quality Infrastructure Law to include PBS in it.

9.2 Auxiliary braking equipment.

Most of the truck tractors being sold in Mexico are manufactured following the US specifications, so they are not equipped with an auxiliary braking system beside the, so called, engine brake. An education process with all stake holders outlining the importance of the auxiliary braking system for the safety on downhill road section should be included in the process.

There should be an incentive for the transportation companies to be able to invest in auxiliary braking systems with the capacity required by this proposed PBS.

9.3 Road signals.

Road signals and procedures must be updated so those road sections which require the use of auxiliary braking systems are clearly identified.

9.4 Implementation schedule.

The schedule to implement the systems should be agreed with the various transportation organizations. Initial demonstration tests should be carried out with the attendance of transportation representatives where it should be clear to them the advantages in safety they will have when equipping their trucks with auxiliary braking systems. Suppliers of the equipment needed should be included in the scheduling process, so there will be enough equipment by the time the PBS becomes mandatory.

9.5 Driver training.

Current driver training schedules should be updated to include the auxiliary braking procedures.

10. Conclusions

The auxiliary braking PBS should be useful to improve road safety on those road section with a downgrade greater than 4% and a length of over 3 km, as it will allow the service brakes to remain cool and thus effective to be used in case of the need to stop the vehicle the soonest in the shortest distance.

Engine brakes installed on tractors manufactured following the common specifications in the US do not have enough power to deal with the steep downhills in Mexico, when vehicle configurations travel at the heavier GVW allowed.

Education and negotiations with transportation representatives are needed to schedule the implementation of the proposed PBS.