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ENERGY BALANCE AND THERMAL PERFORMANCE DURING THE VEHICLE DESCENDING SPEED CONTROL ON ROADS WITH LONG LENGTH STEEP INCLINATION.

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Abstract. *Study on the performance of the retardation systems and the service brakes of commercial vehicles during the descending speed control on roads with long length steep inclination. Mathematical models, based in the equations of the energy balance during the vehicle braking process are used. The thermal performance of the engine, cooling system, and service braking system, are verified for the maximum speeds established for a vehicle travelling downhill. The simulations are performed with programs designed in the Matlab-Simulink platform and with the vehicles following the European norm ECE R13 requirements (test type II A) and the Brazilian norm requirement (NBR 10967) for the downhill functional test (test type III). The obtained results show that it is possible to have a forecast of the dissipated power by the engine and the retarder, of the capacity of dissipated heat of the radiator and other parameters to guarantee the effective speed control of the vehicle, as per the norms requirements, even before the road tests are performed.*

Keywords*: downhill braking, fading, braking thermal analysis, retarder, motor brake.*

1. INTRODUCTION

The vehicle travelling downhill with constant descending speed is a typical example of generation and dissipation mechanical energy into heat. In this case, the kinetic and potential energy, associated with vehicle travelling downhill will have to be transformed into thermal energy and dissipated for the environment through, mainly, the engine's cooling system, the cooling system of the retarder and the vehicle's brake system. In this case, the temperature values of the system's components must not exceed limits of thermal performance failure.

On roads and highways that present long length steep inclination, the requirements with regards to the thermal performance of the vehicle's brake systems are even bigger. Canale et al (2005) show that these conditions of the way can take the brake service system to fading (accented reduction of the braking system performance due the extreme increase of the temperature of its components) if the control of the descending speed have been obtained with the extreme use of the service braking system or insufficient action of the retardation auxiliary systems (motor brake or retarders). This can lead to the lose of the descending speed control or to the emergency braking incapacity which, in both case, will case an serious accident. From that we can see the importance of the vehicle speed control with the retardation of the engine and its auxiliary systems (in case they are available) and/or retarders usually installed in the vehicle's transmission system, in order to control the descending speed. The driver must choose the adequate engaged march to keep the vehicle in the desired or indicated speed, using the service brakes only for small corrections of the descending movement speed (Canale et al., 2007 and Horta Gutiérrez, 2005).

Usually the vehicle brake systems are homologated for these conditions in correspondence with requirements established in the norms (ABNT, 1990, "NBR 10966" and ABNT, 1990, "NBR 10967"). These norms describe the tests of vehicle performance in steep long length downhill (test type II and III (functional test in downhill)). However, not always, test conditions established in the norms correspond to the real road conditions. There is a great diversity of road conditions with regards to inclination, length, sinuosity, etc. For the extreme cases, in which the conditions of the road exceed the inclination values and length established in the norms, it will be necessary to evaluate the vehicle descending performance in the real road conditions and propose new necessary requirements for the tests. These requirements will be, evidently, more rigorous than the actual norms, since they will have to be in correspondence with the road real characteristics.

For these road extreme situations and in the case of heavy long commercial vehicles test, an initial idea on the vehicle's expected behavior during the test is extended important. This allows to prevent the safety, cost, technical requirements and operational logistic of the test and to satisfactory planning and execution of the test. This will to have an initial prevision of the vehicle's capacity to satisfy the norms' requirements. This all justifies the necessity to elaborate and use the computational program for simulation of the vehicle traveling downhill.

For this, mathematical models, based in the equations of the energy balance during the vehicle braking process have been developed. In the model a dependence of brake moment and the dissipated power in the motor brake versus the vehicle speed is considered (Canale, 1989). Also, programs with the Matlab-Simulink platform for the simulation and evaluation of the safety conditions of vehicles traveling on steep long length downhill have been developed.

Now the general aspects of the mathematical models and developed computational programs will be presented. Also some of the results gotten from a study case in which the models and the program had been used to foresee the vehicle behavior before the real test to have an initial notion about the vehicle capacity to satisfying the proposals norms for this case will be shown.

2. ENERGY BRAKE BALANCE OF VEHICLE TRAVELING DOWNHIL

The equilibrium speed in downhill will be that one where the tractor effort given by the mass of the vehicle and the projection of the gravitational field in the direction of the movement is equal to the sum of the forces that resist the movement. In a declivity, this equilibrium allows the controlled constant descending speed of the vehicle. The equilibrium speed depends here of the thermal saturation temperature of brake mechanism. The definition of this temperature value will allow choosing the safety descending gear and speed without the lost of the braking system performance.

The definition of conditions for a vehicle descending safety is developed through the energy balance between the generated energy in the declivity and the dissipated energy in the engine, in the tires and in the retarders (Canale, 1989). The forces that act in a decelerated vehicle on the declivity are shown in the Fig. 1.

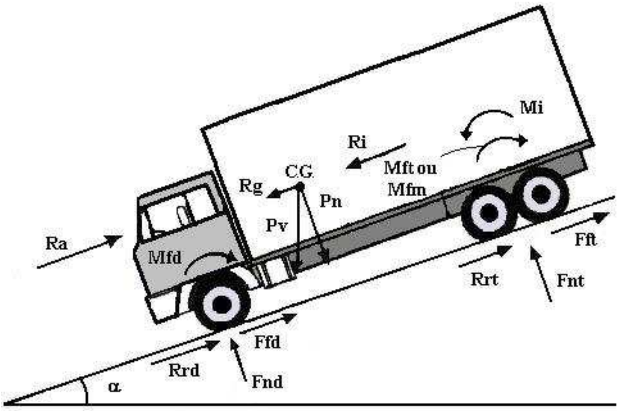

Figure 1 - Forces that act in a decelerated vehicle on declivity.

The forces and moments shown in Fig. 1 are:

- Brake forces in the front and rear axles respectively (Ffd and Fft).
- Rolling resistance force in the tires of each axle (Rrd and Rrt).
- Aerodynamic drag force (Ra).
- Vehicle weight (Pv).
- Grade force (Rg).
- Normal reactions (forces) in the wheels (Fnd and Fnt).
- Inertial force of the decelerated translation mass in (Ri), applied in the vehicle mass center.
- Inertial moment of the rotating parts on the vehicle axles (Mi).
- Brake moment (Mfd and Mft) in the brake mechanisms of the front and rear axles.
- Brake moment of the motor brake or retarder (Mfm).

Expressions for these forces and moments calculation can be seen in Canale (1989), Fernandes (1994) and Lucas (2004). Other mathematical expressions for the stopped distance and time calculation and other parameters of brake performance can be found in these same references.

In the case of the vehicle traveling downhill while decelerating, the brakes will have to absorb kinetic and potential energy as illustrated in Fig. 2.

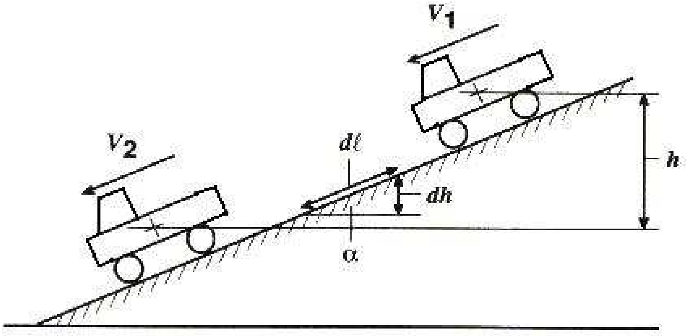

Figure 2 – Kinetic and potential energy in declivity

Using the energy balance (Limpert, 1992), the braking energy (Ef) is:

$$Ef = Pv \cdot h + (k \cdot \frac{m}{2}) \cdot (V_1^2 - V_2^2); \qquad [\mathrm{N \cdot m}] \tag{1}$$

where: Pv – Vehicle weight, N;
h – vertical drop of vehicle, m.
k – correction factor that consider the inertia of the masses in rotation.
m – vehicle mass, kg;
V_1 – initial brake speed, m/s;
V_2 – final brake speed, m/s.

In the case of continued braking with constant speed ($V_1 = V_2$), the Eq. (1) becomes:

$$Ef = Pv \cdot h; \quad [\mathrm{N \cdot m}] \tag{2}$$

Braking power during a continued braking is obtained by energy differentiation with regards to time:

$$Nf = \frac{dEf}{dt} = \frac{dEf}{dh} \cdot \frac{dh}{dt}; \quad [\mathrm{N \cdot m/s}] \tag{3}$$

With the grade expressed by angle α and the actual distance travelled on the highway expressed by ℓ, the change in height and road distance are related to the slope by $\sin \alpha = dh/d\ell$ and the Eq. (3) become:

$$Nf = Pv \cdot V \cdot \sin\alpha; \qquad [\mathrm{N \cdot m/s}] \tag{4}$$

The dependence of the brake moment and the dissipated energy in the engine versus the vehicle velocity (balance energy equation (Canale (1989)) is shown in Eq. (5):

$$Nf + Nm = \frac{V}{745} \cdot (Rg - Rr - Ra); \quad [\mathrm{HP}] \tag{5}$$

where: Nf – dissipated power in the brake, [HP];
Nm - dissipated power by the engine, [HP];
Rg - Grade force, [N];
Rr - Rolling resistance force , [N];
Ra - Aerodynamic drag force , [N];
V – Vehicle speed, [m/s].

The Equation (5) is used in the elaboration of Fig. 3.

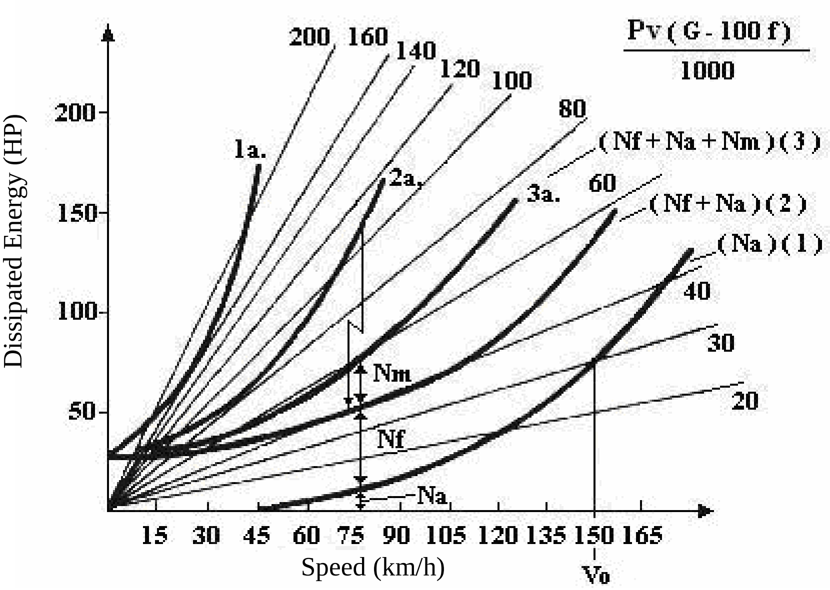

Figure 3 - Thermal balance during the vehicle speed control in the downhill.

The energy balance of Fig. 3 can be verified with the real vehicle test in the downhill. The vehicle must be instrumented and the obtained data can be used for the verification of the energy balance during the permanent regimen movement of vehicle in downhill.

The straight lines of Fig. 3 show the generated energy that depends of road's declivity and the vehicle's weight. The curves indicate the dissipated energy in first, second and third engaged marches (Nm), in the brake (Nf) and by aerodynamic drag resistance (Na). The driver must then choose a descending speed and an engaged march with a dissipated thermal energy capacity larger than the thermal energy generated when the vehicle descent in downhill. With this graph it's possible to obtain the load and operational possible conditions for vehicle descending in downhill.

In some conditions of load and operations, mainly in the case of heavy commercial vehicles, the retardation action of the engine can be insufficient. In these conditions it's necessary the use of auxiliary brake systems (retarders). The electric retarders generate brake moment by the turn of metallic rotor inside of a magnetic field. The generated heat in the rotor is dissipated to the environment through the forced convection by air. The hydraulic retarders are very common used in the very heavy vehicles and generated braking moment is produced by oil that is forced to flow through conduits or caves generating heat and a consequently retardation moment. The resultant thermal energy is dissipated in the radiator on the proper vehicle. A new graphic, based on Fig. 3, can be made including the retarder's action.

Everything previously indicated can be considered in the mathematical model and the simulation program to predict the vehicle performance in any operational condition. Canale et al (2005) show that the evaluation of the transitory effect and the directional stability of the vehicle traveling downhill is difficult by road tests. In this case, the use of simulation program is a mandatory tool for the vehicle performance prevision.

2.1. Mathematical model and computational program.

The mathematical models and the computational programs allow to verify the energy balance during the speed control in the downhill, as well as some aspects of the directional stability of the vehicle by adherence level in the tractive axles. Also allow to simulate the movement of the vehicle with the retardation engine action and with the available retarders. These programs had been developed based in a program developed by Prof. Dr. Antonio Carlos Canale from EESC-USP. Canale's program allows the simulation of a simple two axle's vehicle in any operational condition.

Figure 4 shows some variables that can be directly observed in the initial screen during the simulation: vertical forces on the wheels, angles and angular speeds of the sprung and unsprung mass, lateral slip angle and longitudinal slip percentile of the tires, used adherence, travel space, movement speed, deceleration, etc.

The simulation program considers the following factors: Complete model of the brake system, anti-lock brake system (ABS); non-linear mathematical model of the tires; sprung and unsprung mass; non-linear springs and dampers; suspension geometry; engine retardation action and brake torque developed by electric or hydraulical retarder.

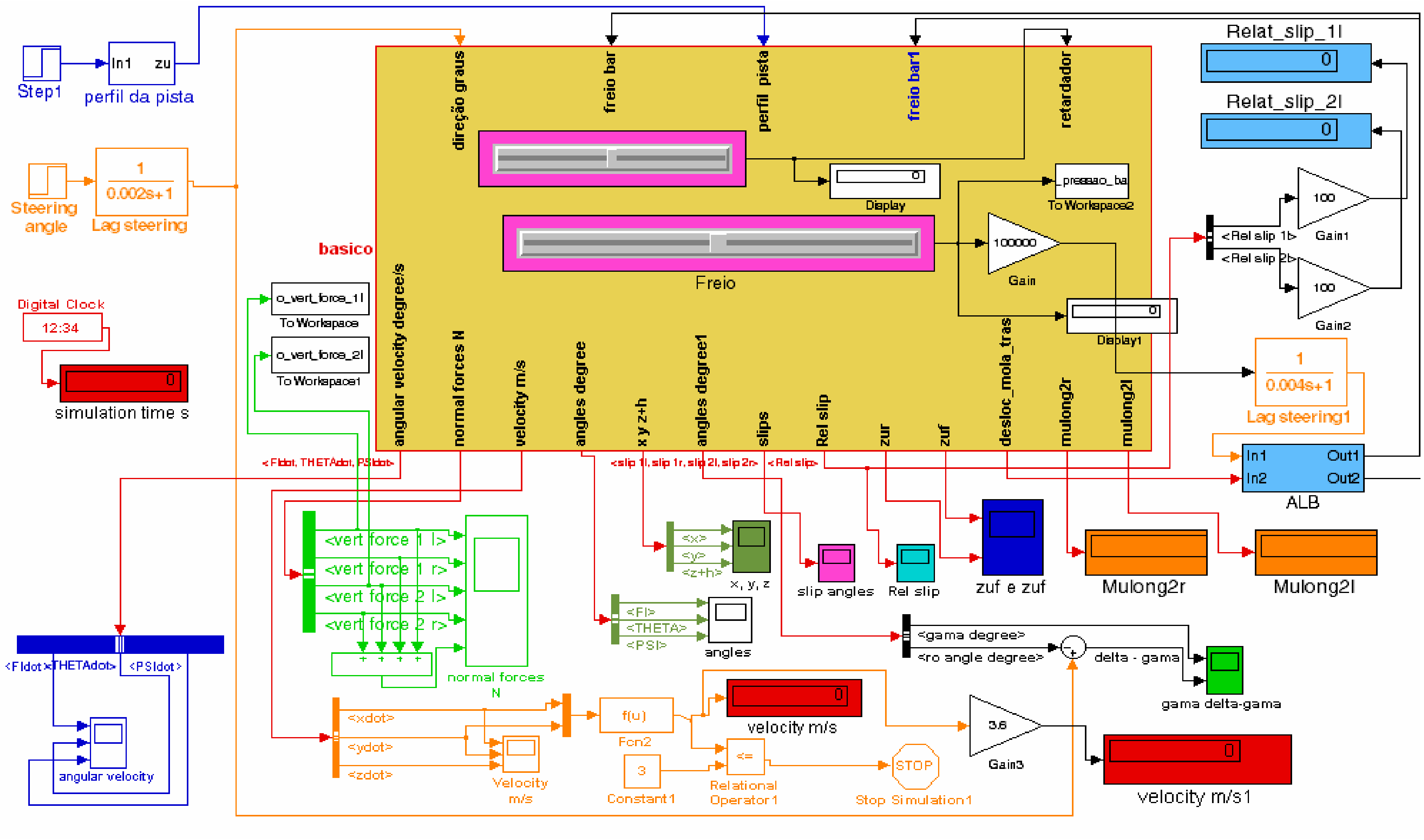

Figure 4 - Initial screen of the simulation program in Matlab Simulink.

The simulations requires multiples vehicle data, the engine retardation power curves (Nm in Fig. 3) and curves of dissipated power for the environment with the brake temperature depending of the vehicle speed (Nf in Fig. 3). It's not possible to simulate the vehicle movement in the declivity and to make the energy balance represented graphically in Fig. 3 without these information.

3. RESULTS

The mathematical models and the computational programs had been used in a study of the braking performance and the descending speed control in the Immigrants highway (in São Paulo, Brazil) which has a long length steep inclination.

In this highway the traffic of commercial vehicles (vans, trucks, buses and combined vehicles) is prohibited by Regulation 11 of 6 of December of 2002 of the ARTESP (Regulating Agency of Public Transport Services of São Paulo State) that can be seen in Horta Gutiérrez (2005). The Highway presents an average declivity of 6,5%, with approach 12 km of length and low sinuosity. Of these 12 km, 9 are inside 3 tunnels of approximately 3 km length each. The specific conditions of this highway are different of the conditions, established in the Brazilian norms, for the homologation of brakes and retardation systems. These specific conditions lead the service brake system to "fading" in the case that the control of descending speed is obtained with the extreme application of the service brake system or insufficient action of the auxiliary retardation systems.

The traffic release of commercial vehicles in this highway will be possible only after technical studies supported by theory and tests evaluation that will allow the verification of the brake performance of representative vehicles of the national fleet. The theoretician-experimental studies about thermal balance during the descending on highway including the evaluation of emergency braking performance, driver's actions, technical vehicle conditions, and adoption of adequate traffic operational model for commercial vehicles in these conditions. The traffic release of commercial vehicles has enormous economic importance because the highway is the best transport connection to the Santos Port, and its use allow the reduction of transportation and exportations costs.

Thus, a complete study was developed including vehicles, drivers, operational model of the highway and technical inspection of vehicles. Computer simulations and real road test were carried to verify the energy balance and the thermal performance during the descending speed control of some types of commercial vehicles. The simulations and the road test were performed as per the European norm ECE R13 requirements (test type II A) and the Brazilian norm requirement (NBR 10967) for the downhill functional test (test type III).

Some results obtained by the simulations of various vehicles categories will be shown as follow. The simulations were splitted in two blocks: results of the simulations of used adherence and results of the simulations with the introduction of the requirements of norms ECE R13 (type II It) and NBR 10967 (type III). They were obtained mainly graph of the used adherence in the tractive axle, vertical forces in the wheels, dissipated power wasted in the motor brake and retarder , speed and space in function of the time and dissipated power by the rolling resistance forces. Here will be shown graphics of dissipated power by the motor brake and the retarder.

Figure 5 shows the graphic of the dissipated power by the engine during the descending of a medium weight vehicle. We can observe that the motor brake allowed to keep the speed controlled in the adopted value (60 Km/h) being capable to dissipate 64 HP without observing extreme heating of the cooling liquid of the engine. The dissipated power by the rolling resistance force was approximately 8 HP (for rolling resistance coefficient (frr) equal to 0,01).

Figure 6 show the graphic of the dissipated power by the engine during the descending of a very heavy weight vehicle (74 tons weight LCV ("Rodotrem")). It is possible to observe that the vehicle keeps the speed controlled in the adopted value (40 Km/h). Here was necessary to dissipate 580 HP. Because the dissipated power is very high, it is necessary to use the retarder. The dissipated power by the rolling resistance force was approximately 110 HP (for frr equal to 0,01).

Figure 7 shows the graphic of the dissipated power in the engine during the descending of a 6 x 2 bus with 20 tons of weight. It is observed that the vehicle keeps the descending speed (60 Km/h) with the motor brake and retarder. Here is necessary to dissipate 250 HP. The vehicle showed satisfactory results.

The obtained results show that it is possible to have a forecast of the dissipated power by the engine and the retarder, of the capacity of dissipated heat of the radiator and other parameters to guarantee the effective speed control of the vehicle, as per the norms requirements, even before the road tests are performed.

The simulations were performed in the Matlab-Simulink platform and with the vehicles following the European norm ECE R13 requirements (test type II A) and the Brazilian norm requirement (NBR 10967) for the downhill functional test (test type III)

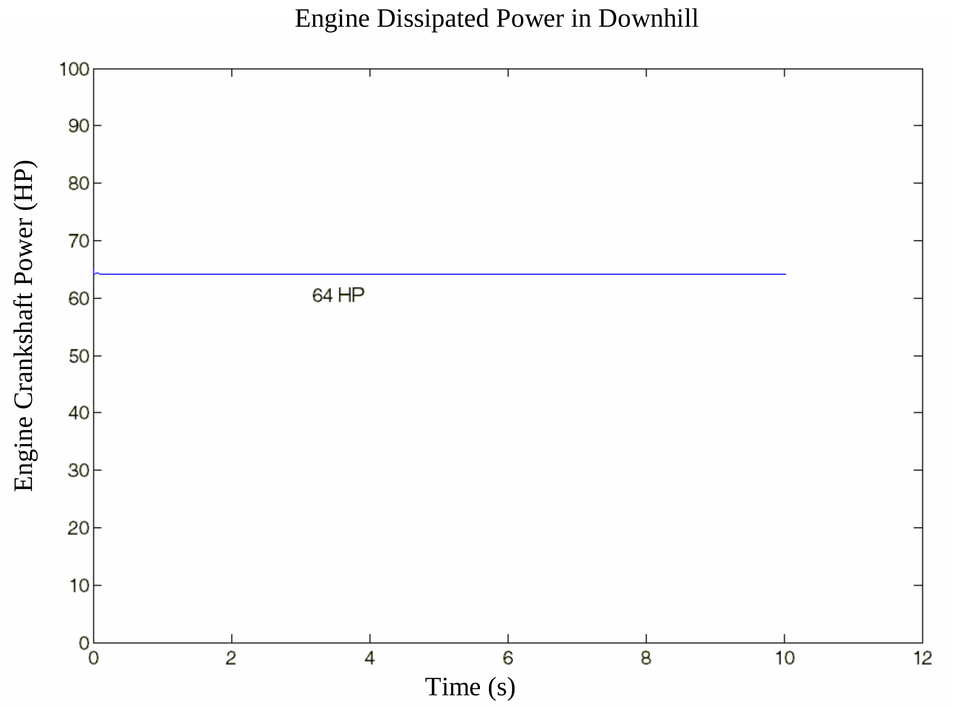

Figure 5 - Dissipated power in the engine during the descending of medium weight vehicle.

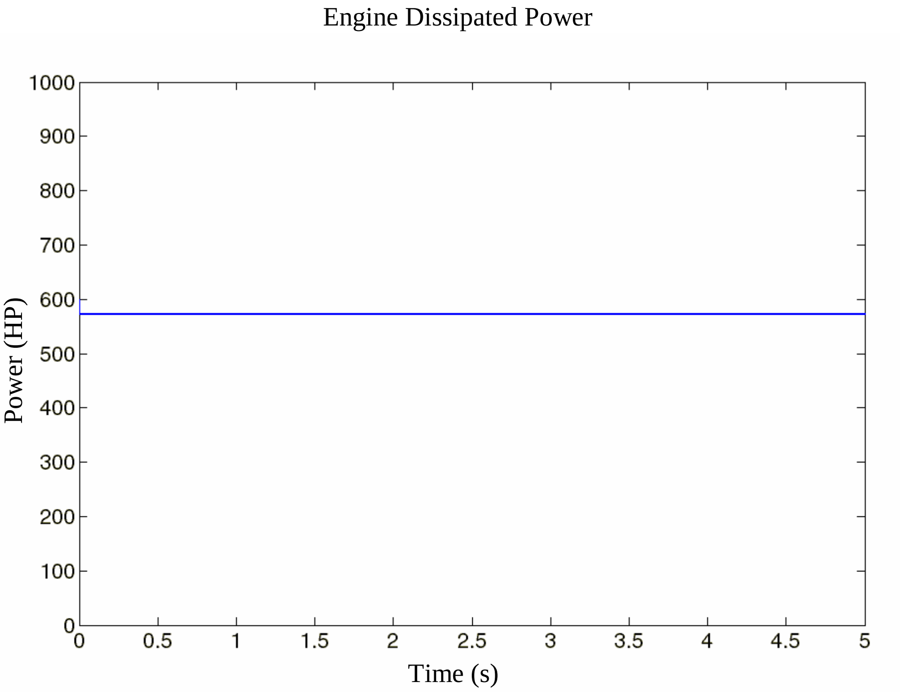

Figure 6 – Dissipated power in the engine and radiator during the descending 74 tons weight LCV.

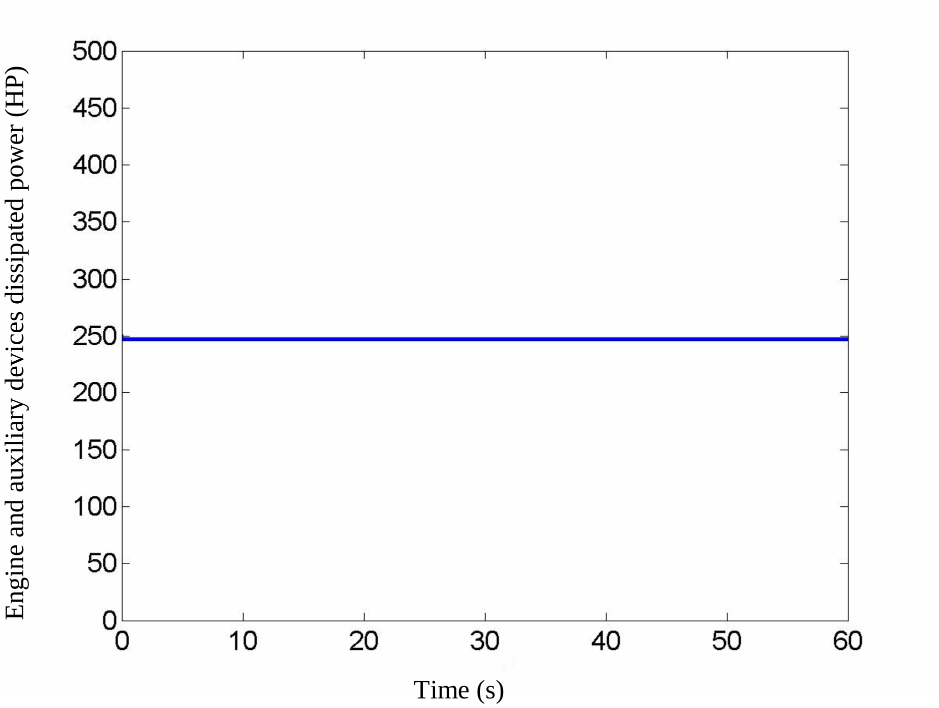

Figure 7 - Dissipated power in the engine and retarder during the descending of a 6x2 bus with 20 tons weight.

4. CONCLUSIONS

The mathematical models and the simulation programs developed to foresee the vehicle behavior in downhill before the real road test had revealed as an efficient tool to predict the vehicle capability to fulfill the proposed norms for this case. Also, they allowed to foresee the adoption of necessary actions to guarantee the security of road test and all the logistic and technical aspects for its accomplishment with effectiveness and reliability.

The simulations had assisted in the vehicle election for the highway test. Through them it was possible to have a forecast of the engine and retarder power, the thermal dissipation capacity of radiator, etc. It is necessary to guarantee the effective speed control for a vehicle safe descending in downhill, as per the initially proposed test norms.

The highway test results were close to the results obtained via theoretical simulation. In general, the vehicles had obtained a good performance during the descending travel, keeping the established speed limits without degradation of control speed system (retardation system). This fact is very important because the highway downhill have a 12 km of length that is greater than the maximum length established in the actual norms (6 Km).

The retardation systems kept its thermal performance and allowed to the driver, a safe vehicle control in the total downhill length, as foreseen in the simulations for all evaluated vehicles. The simulated and tested vehicles that had not totally fulfilled the requirements of the proposed test norms had been very close to this, what indicates that with slight changes in the transmission system, and/or the inclusion of some auxiliary retardation devices and/or the increase of the engine power, the problem can be solved.

In the majority of the tested vehicles, the speed control during the descending was carried by the driver without the use of the service brake. Thus, the cold brake system remains available for use in emergency situations, what allows the increase of the movement safety. However, after the descending, the vehicles had carried the residual brake test in the plane and asphalted part of road as per the norm specification. In general, the tested vehicles had stopped and kept the stability and the control during the braking within the limits indicated in the norm. The residual performance test for the particular case of the long vehicle combinations (LCV) is uncommon, since the manufacturers perform the tests of truck , trailer or semi-trailer separately. Therefore, it was a good chance to evaluate the dynamic behavior of some vehicle combinations under real road test after the initial forecast in computer.

The computer's simulations and road tests had also allowed to indicate necessary technical requirements for commercial vehicles in this highway. From this, the manufacturers will have to certify its vehicles for this highway conditions considering the adequate requirements for this condition. This indicates technical requirements that will have to be considered for future improvement of the actual Brazilian legislation about this subject.

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