PNEUMATIC REGENERATIVE BRAKE EQUIPPED WITH ABS

João Francisco Fleck Heck Britto
Universidade Federal do Rio Grande do Sul, Sarmento Leite, nº 425, 90050-170, Porto Alegre - Brasil
jffhb@terra.com.br

Mauricio Blanco Infantini
Universidade Federal do Rio Grande do Sul, Sarmento Leite, nº 425, 90050-170, Porto Alegre - Brasil
minfantini@yahoo.com.br

Eduardo André Perondi
Universidade Federal do Rio Grande do Sul, Sarmento Leite, nº 425, 90050-170, Porto Alegre - Brasil
perondi@mecanica.ufrgs.br

Abstract. *This study presents a mathematical model of a pneumatic regenerative brake system. Regenerative brakes consist in an alternative to increase the energetic efficiency of automotive vehicles through the conservation of part of the vehicle kinetic energy. A pneumatic system where the energy is stored in an air compressed state is proposed in this work. In this system, the regenerative brake acts in a parallel way with the traditional brake equipped with an anti-lock braking system (ABS). It is shown that the use of an anti-lock braking system (ABS) allow a greater energy saving when compared to passive regenerative pneumatic braking system due to the fact that ABS systems take advantage of the maximum adherence between the tire and the ground avoiding the locking of the wheels. The system is mathematically modeled and designed for an urban bus application. Simulations results allow to conclude that the system with ABS presents energy efficiency advantages when compared to passive brake.*

Keywords: *regenerative braking system, energy efficiency, passive braking, ABS braking, automotive vehicles.*

1. Introduction

Regenerative brakes are those who conserve dynamic energy, transforming it in potential energy for subsequent application. The traditional brakes are friction based and dissipate the dynamic energy, having important losses in the energy efficiency of the global system. Fossil fuels reserves are limited and high investments are made by companies, institutes and universities in research for its substitution and creation of more efficient systems. The technology of regenerative brakes is in agreement with this tendency.

Nowadays, there are few known commercial applications of regenerative brake systems. However, there are many researches and studies that seem to be still insufficient for its extensive application. Most of the regenerative brakes studied are electrical. These systems are based on the use of electrical generators and chemical batteries and are s usually present in hybrid vehicles (Otto motors and electric motor) and electric trains.

In this work it is evaluated the performance of a regenerative system based on pneumatics and designed for an urban bus equipped with ABS. The proposed system consists of a pneumatic compressor linked to the transmission system. When the braking action happens, the compressor is started and the compressed air is stored in a pressure vessel for subsequent use in other applications. Studies performed by Britto (2004) indicate losses in passive braking because of braking inefficiency due to wheels locking. So, it was attached an ABS model to increase the regenerative braking efficiency. Simulations in passive and ABS braking were performed with the regenerative brake system to determine the gain obtained with the ABS action.

The ABS control logic is presented briefly in the section 5. Studies proved its considerable efficiency for passenger vehicles (see Infantini, 2003, for example). More details about the ABS control logic can be obtained in Semmler et al. (2004).

2. Regenerative Brake Systems

Brake systems of most standard automobiles convert kinetic energy in heat that is dissipated to the atmosphere. The process of brake activation can be divided into two thermo dynamical phases: the friction phenomena and the cooling system. In the first phase, the energy of the movement is converted to calorific energy thorough temperature increasing. In the second phase, the heat is transferred from the brakes to the surrounding ambient, cooling the brake system.

It is quite easy to describe the qualitative benefits due to the use of regenerative brakes in vehicles. On the other hand, it is not so easy to accomplish quantitative data to demonstrate it. An analysis in this sense should involve requirements of vehicle potency as a function of the transport cycle to determine the energy ratio that can be absorbed and stored by the brakes. Wicks and Donnelly (2002) determine the work cycle for an urban bus and perform a regenerative brakes application potentiality analysis. They show that the portion of 91% of total energy is wasted by the brakes, being the remaining energy dissipated by the air and tire-soil frictions. It is also verified that 59% of the work produced by the motor is consumed by the brakes, being, in an ideal situation, the potential of energy economy. These results indicate a clear justification for the research lines in this area.

Today, the most advanced studies are in the application of electric regenerative systems. This technology is mainly based in the use of the speed difference between a rotaries axis and a fixed magnetic field that induces the appearance of electric current. Previously, in the former designs, the current induced during the activation of the brake in electric motors was dissipated in benches of resistors by Joule effect, wasting the energy. Due to the technological progress of electronics and control techniques, it is possible today to absorb and store this current.

In Flinders, Mathew and Oghanna (1995) it is presented the use of regenerative systems in trains based on modern tiristores GTO which allows high potency rectification. The regenerative system, used in the north track of New Zealand railroad, guarantees an energy economy of 13%. In the same paper, it is also shown the measurement of energy losses during the application of dynamic brakes in the main line of Central Queensland. In this railroad, the coal is transported from the mines located 400 km to the west. The total energy wasted during the brakes activation is 8,7 MWh. Taking into account the whole process during a year, approximately 100 GWh are wasted.

Besides its application in trains, regenerative systems are used in hybrid electric vehicles (HEV), where there is an electric motor as potency's source coupled to the combustion motor. This vehicle conception presents other advantages, as smaller dimensions and weights and the appropriate rotation control of the combustion motor, causing fuel economy and emissions reduction (He and Hodgson, 2002). Panagiotidis, Delagrammatikas and Assanis (2000) report fuel savings of 15% in some HEV vehicles configurations. These are values much more conservatives than the ideal 59% presented previously, but are still very significant concerning energy efficiency performance. The advanced technology involving hybrid vehicles limits its application to few commercial models.

The technology adopted in this study is alternative because it is proposed the use of a system flow-mechanic as regenerative brake. In addition, an ABS is attached to the system to improve the regenerative brake efficiency.

3. Regenerative Brake Design

This paper reports the design of a pneumatic regenerative brake system to be applied in a commercial vehicle equipped with ABS brake system. The proposed pneumatic system must be installed in parallel to the ABS, seeking global energy efficiency improvement. Therefore, it is necessary to define a system with potential and viability for its application and to study the energetic efficiency with the regenerative system integrated. The efficiency study is done thorough simulations using a vehicle dynamic's model equipped with ABS and integrated with the regenerative system model. A private transport vehicle (urban zone bus) which works with compressed air to execute some actions as automatic door driving and air brake driving system was used as basis to the new brake system proposed.

The equations' solutions that establish the dynamic system behavior is performed through the use of the numerical integration software Matlab® (2002). Through the Simulink module, the diagrams of block are built and the set of associated differential equations is solved. The simulations results allow the verification of the influence of the regenerative system in the dynamic behavior and determine the energetic efficiency.

The parameters of the dissipative brake were defined so that the system behavior is in accordance with the Brazilian National Standard (ABNT, 2004). The regenerative brake system was incorporated in a way that the modified system maintains the same operational and functional characteristics of the previous system. The simulations were performed using a private transport cycle model. The results were analyzed considering the energy savings in the braking process with and without antilock action.

Automotive vehicles can be used in several environmental conditions, so their requirements can vary significantly. The energy consumed in a vehicle is mainly due to the resistance of the air, to the friction of the tires with the soil and the internal friction of the movable parts, besides the amount consumed by the brakes. Therefore, it is not appropriate the use of a regenerative system for vehicles that travel wide distances because the braking action is not frequent in this operational situation. Smaller vehicles have spacial restrictions, hindering the application of the proposed pneumatic regenerative system. So, the most appropriate vehicles for the implantation of the system are buses and urban trucks that have intense accelerations cycles and, consequently, considerable efficiency losses caused by the frequent brakes activation. This is the main situation usually addressed in the electric regenerative brakes bibliography. Therefore, it was convenient the choice of an urban bus working in the city of Porto Alegre (RS - Brasil).

The proposed regenerative brake system is constituted by a compressor, a pressure vessel and a clutch that links the transmission axis and the compressor. It was chosen an alternative double action piston-type compressor. In this initial proposal only the back wheels of the vehicle are coupled to the regenerative brake system. The proposed system to be installed in a vehicle is presented in Fig. 1. When the brake pedal is activated, the vehicle transmission system separates the motor of the transmission train. Through a clutch, the compressor is linked to the vehicle transmission axis. So, the compressor starts the process of pumping air to the vessel, generating an opposite torque to the motor axis. At this time, the dissipative brake is also working, and the two systems act together, slowing down the vehicle. The traditional electric regenerative systems are similar.

4. The Regenerative Model

The system is modeled mathematically for the evaluation of its dynamic behavior. Some considerations are carried out to simplify the problem during the simulation, such as: the compressor and the transmission start coupled while the motor is uncoupled of the vehicle transmission. This determines the initial instant of the simulation with null acceleration and constant velocity of the vehicle.

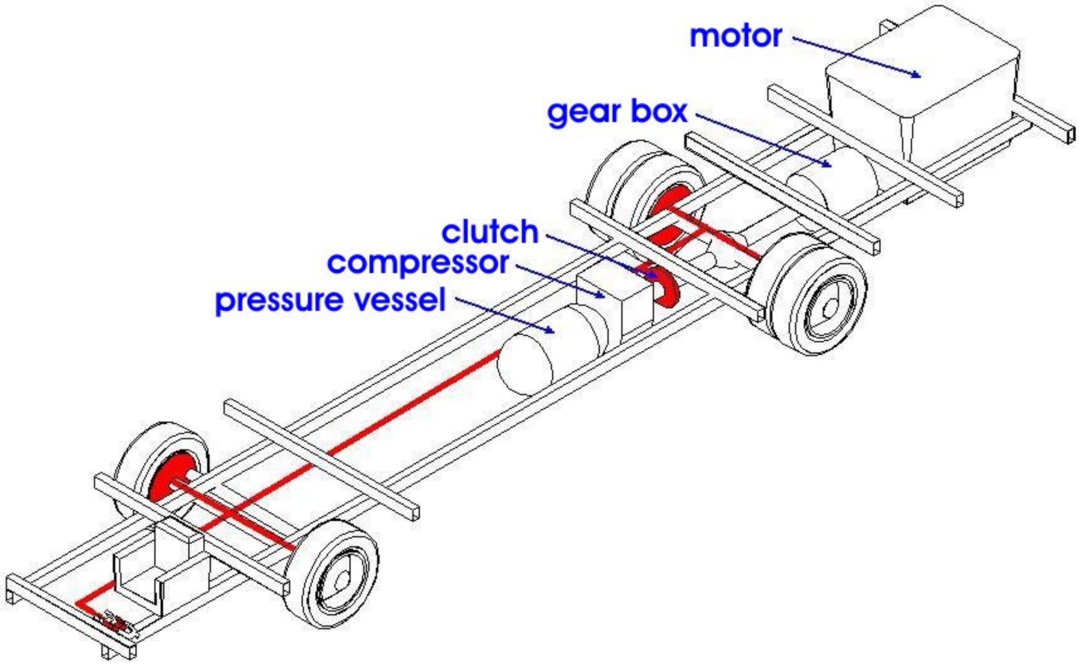

Figure 1 - Sketch of the proposed regenerative brake system

The objective is to study the energy saving with the regenerative brake in respect to the traditional brake system equipped with ABS. The free body diagram is presented in the Fig. 2.

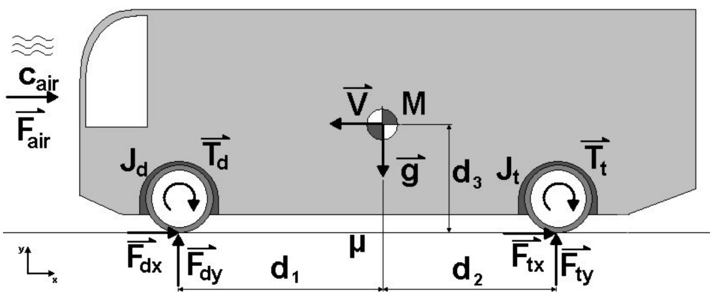

Figure 2 – Vehicle free body vehicle diagram

From the free body vehicle diagram it is determined the equilibrium's equations. The horizontal forces can be expressed through Eq. (1):

$$M\frac{d^2x}{dt^2}+C_{air}\frac{dx}{dt}+F_{dx}+F_{tx}=0 \tag{1}$$

where M is the vehicle mass, C_{air} is the damper coefficient of the air, F_{dx} and F_{dy} are the reactive forces of friction between the tire and the soil.

In the vertical direction, it can be expressed as

$$F_{dy}+F_{ty}-Mg=0 \tag{2}$$

where g is the gravity acceleration, F_{dy} is the front reaction force in the vertical direction and F_{ty} is the back reaction force in the vertical direction. The moment caused by the contact forces with the soil by the front wheels are described by

$$\left(M\frac{d^2x}{dt^2}-C_{air}\frac{dx}{dt}\right)d_3-Mgd_1+F_{ty}(d_1+d_2)=0 \tag{3}$$

where d_1 is the gravity center distance to the front axis and d_2 is the gravity center distance to the back axis. The moment in the back wheels can be described by

$$-J_t\frac{d^2\theta}{dt^2}-T_b-C_{ang}\frac{d\theta}{dt}+F_{tx}r_t=0 \tag{4}$$

where T_b is the torque due to the application of the brake, J_t is the polar moment of inertia in respect to the rear axis, C_{ang} is the angular friction dumping coefficient and r_t the radius of the back tire.

The horizontal forces F_{tx} and F_{dx} are proportional to the contact friction coefficient and to the normal forces F_{ty} and F_{dy}, respectively. The force F_{tx} is expressed by

$$F_{tx}=\mu F_{ty} \tag{5}$$

The adherence μ is a function of many parameters like environment conditions, vertical loads, surface types, translation speeds and internal pressures of the tires.

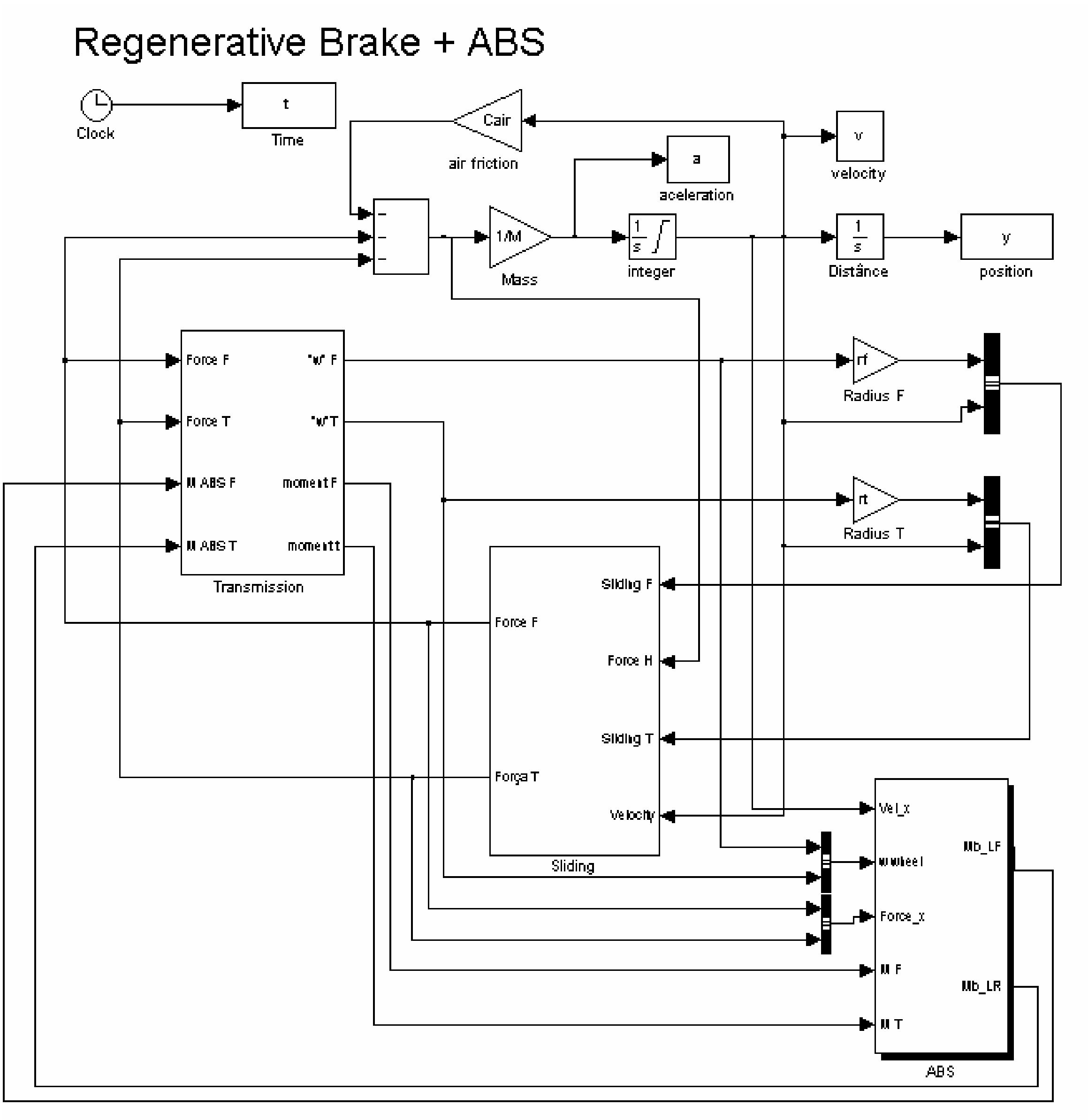

Figure 3 – Main Block Diagram of the Model

The diagram of presented in the Fig. 4 displays the brake system's model. This block is in the transmission subsystem block.

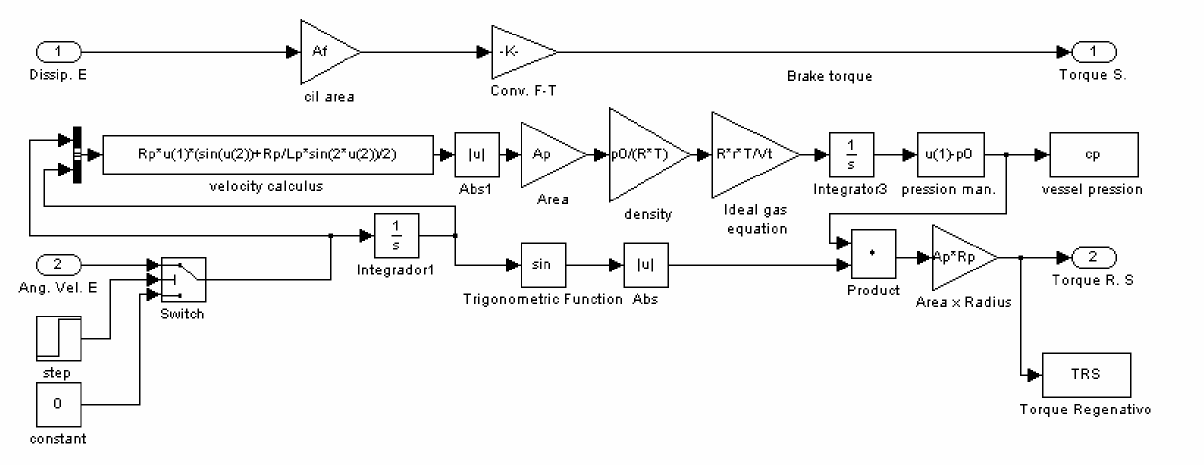

Figure 4 – Block diagram of the brake system

In the superior part of the block the equations from the drum brake are presented, usually used in heavy vehicles. The hydraulic pressure brake is multiplied by the actuator cylinder area, resulting in the equivalent force. This force, through the equation for drum brake found in Gillespie (1992), results in the equivalent torque.

In the inferior part of the Fig. 4 the diagram of block of the regenerative brake is presented. It is modeled through the analysis of the free body diagram, presented in the Fig. 5.

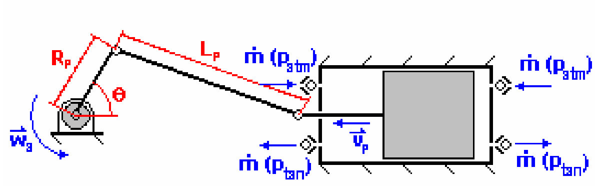

Figure 5 – Free body diagram of the regenerative brake system

The mass and the moment of inertia of the ensemble are neglected, therefore they are small compared to the total mass of the vehicle. The relationship between the axis rotation velocity w_a and the piston translational velocity v_p is presented in the Eq. (6), according to Mabie (1980):

$$v_p = -R_p w_p (sen\theta + \frac{R_p sen2\theta}{2L_p}) \tag{6}$$

where R_p is the radius of the crank, L_p is the length of the connecting rod and θ is defined according to Fig. 5.

The relationship between the mass flow *dm/dt* and the translational velocity is presented in the Eq. (7):

$$\dot{m} = -\rho A_p v_p \tag{7}$$

where ρ is the density of the atmospheric air and A_p is the piston area. The pressure variation in the tank for the injection of this mass flow, being considered as an adiabatic isentropic process and with small temperature variation, is obtained through Perondi and Guenther (2003) and is presented in Eq. (8):

$$\frac{dp}{dt} = \frac{RrT}{V_t}\dot{m} \tag{8}$$

where R is the constant of the air, r is the relationship among specific heats, T is the temperature and V_t is the volume of the pressure vessel. This pressure variation, integrated along the time, represents the reactive pressure against to the piston movement. It is this effect that causes the vehicle's regenerative braking. The work done to insufflate air into the camera is neglected when compared to the compression work. The reactive equivalent torque is presented in Eq. (9):

$$T_{regen} = pA_p R_p sen\theta \tag{9}$$

This torque is added to the torque applied by the traditional dissipative brake in a braking condition. These equations are transformed in the diagram of block presented in the Fig. 4, where the presence of the bracket represents the instant of the system starting. The pressure is then accumulated in the tank. The elastic potential energy accumulated in the pressure vessel is the saved energy by the regenerative system. It is expressed by the Eq. (10):

$$E = pV_t \tag{10}$$

5. ABS Control Logic

To design a system to control the wheel slip it is necessary to take into account the behavior of some system parameters and variable, such as torque supplied by the engine (T_a) and by the brakes (T_b), the longitudinal force (F_x) that acts on the wheel, and the polar moment of inertia (J). Equation (11) supplies the equilibrium expression of the torques applied on the wheel:

$$J\dot{w} = r_{dyn}F_x - aF_y - T_f + T_a - T_b \tag{11}$$

where r_{dyn} is the wheels radius, w is the rotational velocity, F_y is the normal force on the wheel and T_f is the bearing friction toque. Figure 6 presents a graphic interpretation of Eq. (11):

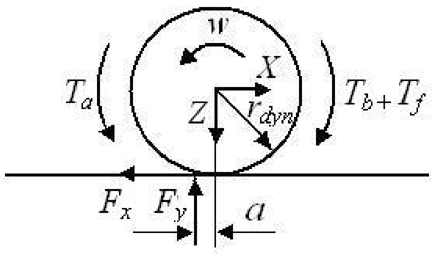

Figure 6 – Forces and torques acting on the wheel

The term $aF_y + T_f$ can be substituted for:

$$T^* = aF_y + T_f \tag{12}$$

Then, Eq. (11) can be rewritten as:

$$J\dot{w} = r_{dyn}F_x - T^* + T_a - T_b \tag{13}$$

The torque T_b applied on the wheel, given by Gillespie (1992), is expressed by Eq. (14):

$$T_b = \left(\frac{\lambda e}{m - \lambda n} + \frac{\lambda e}{m + \lambda n}\right)F_a r_r \tag{14}$$

where λ is the friction coefficient between the drum and the brake lining, e is the perpendicular distance between the actuator and the pivot, n is the perpendicular distance between the friction force line and the pivot, m is the perpendicular distance between the normal force and the pivot, F_a is the force in the drum actuator and r_r is the drum radius. The wheel slip (S) is defined according to the case studied: braking or acceleration of the wheel. In the case of braking, it is:

$$S = \frac{v - wr_{dyn}}{v} \tag{15}$$

Based on equations (12) to (15), Semmler et al., (2003) propose a control law based on a proportional derivative (PD) control loop on S. The following expression for T_b is proved to be able to keep the wheels closed to the desired slip (S_d).

$$T_{b(ABS)} = T_a + r_{dyn}F_x - \frac{J\dot{v}}{r_{dyn}}(S - 1) + \frac{Jv}{r_{dyn}}\xi \tag{16}$$

where the PD control signal ξ is given by

$$\xi = k_p(S_d - S) + k_d(\dot{S}_d - \dot{S}) \tag{17}$$

and v is the wheel longitudinal velocity, k_p and k_d are, respectively, the proportional and derivative gains.

6. Results

Some simulations were performed for a vehicle's initial velocity of 60 km/h and an adherence between tire and ground of 0.9. The tests compare the gain obtained in the regenerative brake system with the ABS action over passive braking. The driver starts braking at 0s.

The initial tests showed that the increasing of energy stored by the ABS brake when compared to the passive brake is around 15%, as it can be verified in Fig. 7. In this test, the brake pedal is activated until achieves the end of the brake travel in 2s, it remains activated until the vehicle stopping. In Fig. 8 it is observed the locking of the wheels for passive braking. In ABS braking the wheels are not locked, however, there is a delay in the wheel slip convergence to the desired wheel slip. It is due to the brake system pressure that is relatively low for the appropriate ABS operating. Once the wheel slip achieves the desired wheel slip, it maintains closed to it until the vehicle stop. The pressure brake system was dimensioned to take into account the INMETRO resolution that establishes a minimum braking stopping distance of 36m (Instituto Nacional de Metrologia, Normalização e Qualidade Industrial, 2004).

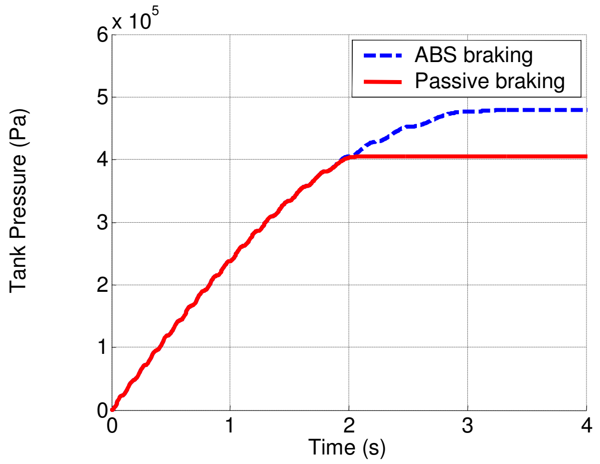

Figure 7 - Tank pressure for ABS and passive brakes – low pressure case.

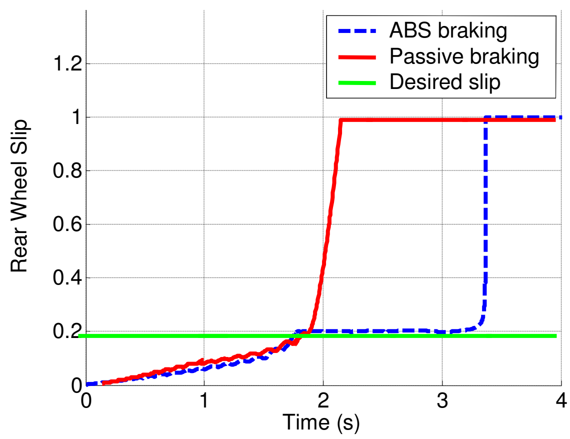

Figure 8 - Wheel slip behavior - low pressure case.

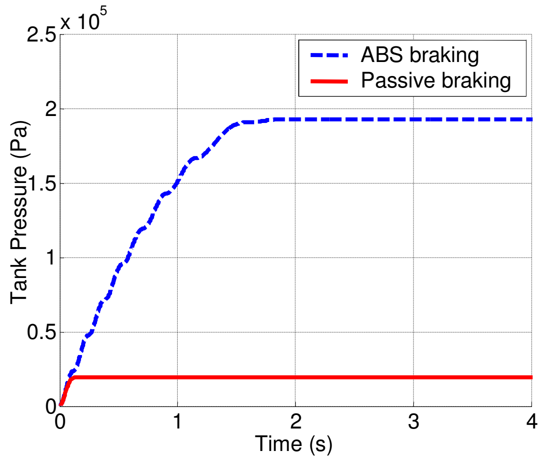

Figure 9: Tank pressure for ABS and passive Braking - high pressure case.

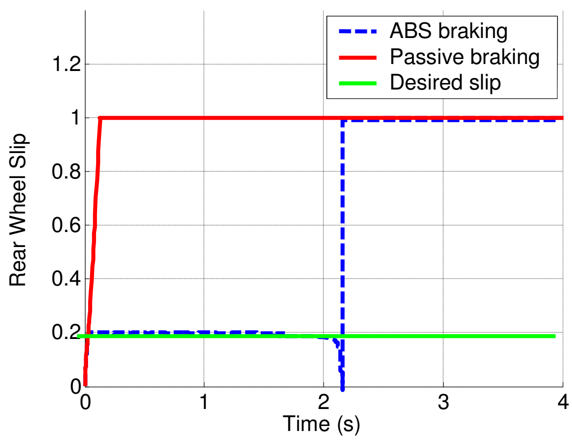

Figure 10 - Wheel slip behavior - high pressure case.

In order to improve the ABS operating, the brake system pressure needs to be higher than in the passive case, as well as the velocity that the brake pedal is activated and, if it is considered an emergency braking situation, the brake force goes almost instantaneously to its higher level, about 0.5 s.

Figure 9 shows an improvement of 860% for ABS braking over passive braking in terms of energy stored. In relation to Fig. 7, it is observed a reduction of 60% in energy stored for the high pressure brake system adjustment. This reduction is justified by the considerable lower stopping distance in this new ABS braking condition. Fig. 10 shows the locking of the wheels for passive braking as it was expected. In ABS braking, the wheel slip reaches the desired wheel slip quickly pursuing it until the vehicle stop.

Figure 11 shows that the ABS braking allows the vehicle stopping before in time than in passive braking condition. Figure 12 shows the considerable reduction in stopping distance obtained with the ABS.

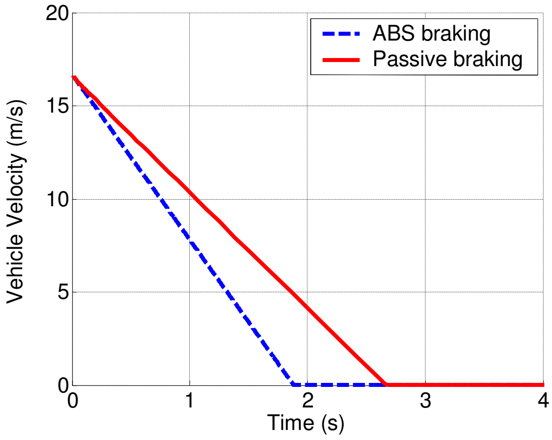

Figure 11: Vehicle velocity

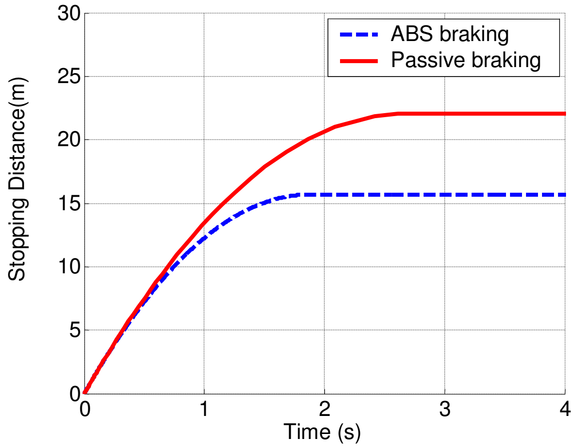

Figure 12: Stopping distance

7. Conclusion

In this paper, the modeling of a pneumatic regenerative brake equipped with ABS is presented. The simulations performed with the model show that the use of an ABS brake system would improve the pneumatic regenerative brake system performance when compared with passive braking. The ABS system avoids the wheels locking, allowing a more efficient activation of the compressor by the transmission system. The results show the considerable improvement in pressure stored when ABS braking is used and also that the performance of the regenerative brake system is dependent on the passive brake system pressure adjustment.

Further studies will include simulations to study the influence of the pneumatic regenerative brake system in the mechanical brake system heating, which is a source of one of the main trouble in actual brake systems applied to heavy vehicles. As, in the case of regenerative brakes, the regenerative system stores part of the kinetic energy of the vehicles, less energy will be dissipated by Joule effect in the friction braking process. So, the mechanical brake system will have his heating curve changed, and as it is known, the process involving the material abrasion effectiveness properties and the system temperature presents a nonlinear behavior, the gains in breakability could be significant with regenerative brakes. This fact, allied to the energy saving, could justify real industry investments in this area.

8. References

Britto, J. F. F. H., 2004, “Freio Regenerativo Pneumático”, Trabalho de Conclusão de Curso - UFRGS, Porto Alegre, RS, Brasil.

Flinders, F., Mathew, R., Oghanna, W., 1995. “Energy Savings Through Regenerative Braking Using Retrofit Converters”. Central Queensland, Australia.

Freitas, S. L. O., Cardoso, G., Júnior, J. L. F. 2002. “Análise das características geométricas de corredores de ônibus: estudo na cidade de Porto Alegre, RS”. Porto Alegre.

Gillespie, T. D., 1992. “Fundamentals of Vehicle Dynamics”. Warrendale: Society of Automotive Engineers, Inc,

Infantini, M. B., 2003, “Automotive Braking Systems Experimental Test and Virtual Modeling”, Politecnico di Torino, Turin.

He, X., Hodgson, J., 2002, “Modeling and Simulation for Hybrid Electric Vehicles – Part I”: Modeling, IEEE Transactions on Intelligent Transportation Systems. vol. 3 no. 4.

Instituto Nacional de Metrologia, Normalização e Qualidade Industrial, 2004. “Portaria n.º 30”. Brasília.

Mabie, H. H. 1980, “Mecanismos”, LTC 2.ed. Rio de Janeiro: LTC,.

Maclay, D., 1997, “Two DOF Vehicle Suspension Model”. Cambridge:.

Panagiotidis, M., Delagrammatikas, G., Assanis, D., 2000, “Development and Use of a Regenerative Braking Model for a Parallel Hybrid Electric Vehicle”. Ann Arbor:.

Perondi, E. A., Guenther, R., 2003 “Modelagem de um servoposicionador pneumático com atrito”. Ciência & Engenharia. Uberlândia: , v.12, n.1, p.43 - 52,.

Semmler, S., Isermann, R., Schwarz, R., and Rieth, P., 2003, “Wheel Slip Control for Antilock Braking Systems Using Brake-by-Wire Actuators”, SAE, Warrendale.

Wicks, F., Donnely Y, K, 2002, “Modeling Regenerative Braking and storage for vehicles”, New York.

9. Responsibility notice

The authors are the only responsible for the printed material included in this paper.