International Journal of Automotive Technology, Vol. ?, No. ?, pp. ?−?(year)

Serial#Given by KSAE

ELECTRO-HYDRAULIC BRAKING SYSTEM FOR AUTONOMOUS VEHICLES

V. MILANÉS[1)*], C. GONZÁLEZ[1)], J.E. NARANJO[2)], E. ONIEVA[1)] and T. DE PEDRO[1)]

[1)]Instituto de Automática Industrial (IAI-CSIC), Crta. Campo Real km. 0.200, Madrid 28500, Spain
[2)]Escuela Universitaria de Informática (UPM), Crta. Valencia km. 7, Madrid 28500, Spain

(*Received date 25 January 2008 ; revised date 8 April 2009*)

ABSTRACT−Reducing the number of traffic accidents is a declared target of most governments. Since dependence on driver reaction is the main cause of road accidents, it would be advisable to replace the human factor in some driving-related tasks with automated solutions. In order to automate a vehicle it is necessary to control the actuators of a car, i.e., the steering wheel, accelerator, and brake. This paper presents the design and implementation of an electro-hydraulic braking system consisting of a pump and various valves allowing the control computer to stop the car. It is assembled in coexistence with the original circuit for the sake of robustness and to permit the two systems to halt the car independently. This system was developed for installation in a commercial Citroën C3 Pluriel of the AUTOPIA program. Various tests were carried out of its correct operation, and an experiment showing the integration of the system into the longitudinal control of the car is described.

KEY WORDS: Electro-hydraulic brake, road vehicle control, autonomous systems, safety road, transport systems.

1. INTRODUCTION

Most road accident victims are not the motor vehicle's occupants, but pedestrians, motorcyclists, bicyclists, and non-motor vehicle (NMV) occupants (World Health Organization, 2004). The main problem is the driver's difficulty in reacting quickly to unexpected circumstances. To solve this problem, semi-autonomous systems such as antilock or emergency braking systems have been developed and tested (Cummings, 2007; Petersen, 2006). Even so, the human factor continues to play a key role.

Intelligent Transportation Systems (ITS) (Wang, 2005) focus on improving safety and reducing transportation times and fuel consumption. One part of ITS is autonomous vehicle guidance. This uses two controls. One is lateral control (Naranjo, 2005; Ryu, 2007) which is associated with the steering wheel, and the other is longitudinal control (Liang, 2003; Gerdes 1997) involving the throttle and brake pedals as actuators.

Throttle control is necessary for guidance, while brake control is essential in the security functions needed to avoid collisions, including emergency stops (Yi, 2002), "Stop&Go"(Naranjo, 2006), adaptive cruise control (ACC) (Naranjo, 2006), pedestrian detection (Li, 2006), lane keeping (Wang, 2005), and blind angle perception (Collado, 2004).

In order to develop an automatic braking system, one has two options: modify the original circuit or design a new system to work in coexistence with the original. The second option allows increased safety since the braking system is duplicated.

The system behaviour of brake automation has been modelled by several authors. Celentano (Celentano, 2003) proposes a simple but realistic brake system model based on a division into four subsystems, taking the model's parameters to be those of a Fiat car. Song (Song, 2006) adds braking pressure feedback to an antilock braking system (ABS), with simulation results proving that the algorithm is able to recognize road surface changes. Song (Song, 2004) proposes a new hybrid electric brake system, with simulation results showing a reduction in stopping distance with less electric power consumption. Liang (Liang, 2003) significantly reduces the speed and space braking error

* *Corresponding author*. e-mail: vmilanes@iai.csic.es

during large braking processes. Jung (Jung, 2008) has developed a program to analyze different variables (pressure, efficiency, and pedal travel) associated with the braking of a vehicle.

In a parallel line of work, different controllers for the braking system have been developed. Lignon (Lignon, 2006) uses a robust control in order to eliminate friction-induced vibration to obtain stability under all operating conditions. Maciuca has designed a non-smooth controller (Maciuca, 1997) and an adaptive controller (Maciuca, 1998) to be applied to the control of brake systems in an automated highway environment. Hong (Hong, 2006) designs a wheel slip controller based on the sliding mode control method that is able to control the braking force more precisely, and can be readily adapted to different vehicles. Park (Park, 2006) proposes a different system for the hydraulic brake system based on a magneto-rheological brake design. Kang (Kang, 2004) designs an emergency braking control system for short distances of cars in platooning.

With respect to experimental results, Gerdes (Gerdes, 1997) tested a combined engine and brake controller for automated highway vehicles based on the idea of multiple-surface sliding control in a car. Kim (Kim, 1996) used the control of an original brake system by means of an actuator. Naranjo (Naranjo, 2006) applied an encoder coupled to a dc motor in the original circuit to obtain an automatic braking system pulling on the brake pedal. Song (Song, 2005) connected an electrical brake actuator in parallel in order to generate additional brake pressure in the pneumatic brake system of a bus, and Bu (Bu, 2007) developed a pneumatic brake used to accurately halt buses in a station.

The AUTOPIA project has been working on the development of automatic vehicles for over ten years. While the long term goal of achieving an automatic car may be unreachable in the near future, the systems that have been developed for automatic driving have uses as Advanced Driver Assistance Systems (ADAS). The present communication describes the implementation of a new automatic braking system design. It is an electro-hydraulic system consisting of a pump and various valves allowing the control computer to stop the car. It is assembled in coexistence with the original circuit for the sake of robustness and to permit the two systems to halt the car independently. The goal is to have an automatic system capable of activating the brake of a car by emulating a human driver while not interfering with the already existing braking system.

The paper is organized as follows. Section 2 presents the design of the automatic brake system. Section 3 explains the system's installation in our Citroën C3 Pluriel. Section 4 describes the tests performed to evaluate the system and compare it with a human driver. Section 5 presents the integration of the brake with a fuzzy control system, and Section 6 gives some concluding remarks.

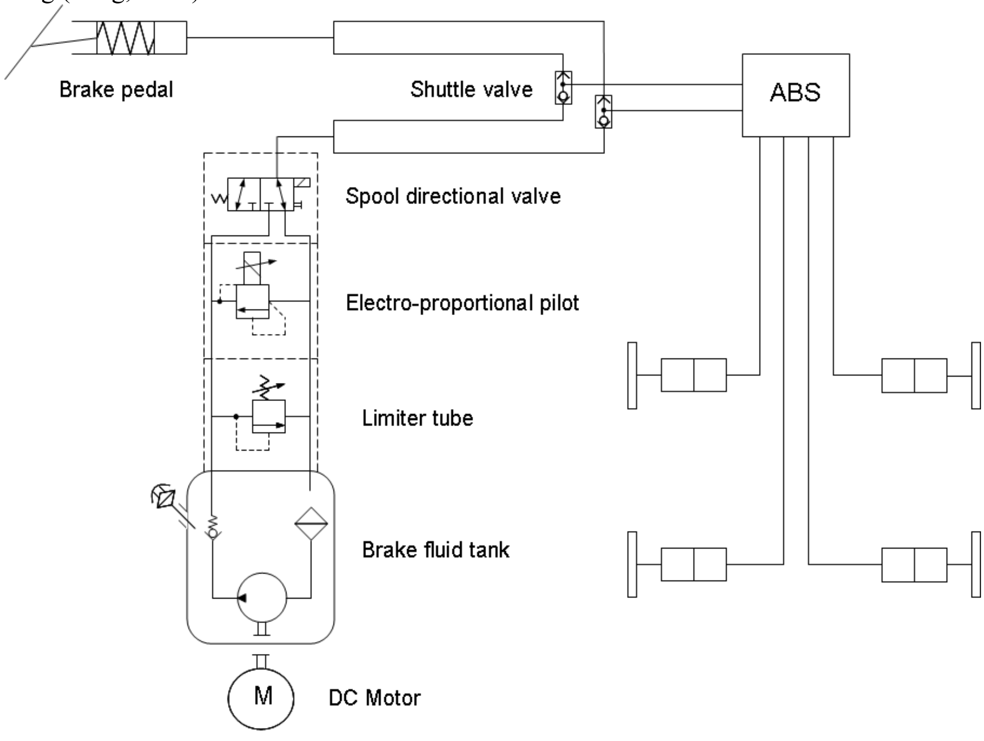

Figure 1. The braking system design.

2. BRAKING SYSTEMS DESIGNED

The AUTOPIA C3 Pluriel was already automated, but with only the steering wheel and accelerator controlled. Speed control was good as long as sudden changes in speed were not required. Thus, the necessary next step was to design and implement a braking system. This system would have to be capable of operating as a minimum at the AUTOPIA control sampling rate, which was set by the GPS at 5 Hz.

The main prerequisite was to obtain a brake by wire system in coexistence with the original braking system. The solution decided on was to design a hydraulic system equipped with electronic components to permit handling by computer generated signals through an input/output device.

Before proceeding with the design, it was necessary to determine the maximum braking pressure in order to avoid excessive system stress. This datum was determined experimentally by means of a manometer. A wheel was removed, and a manometer was connected in lieu of the brake shoe. A pressure of 160 bars was measured when the brake pedal was completely pressed down.

The hydraulic system consists of a one-litre capacity brake fluid tank that includes a gear pump and coupling to a 350-watt, 12-volt supply, dc motor. A pressure limiter tube whose value is fixed at 160 bars is added in order to protect the car elements involved in the braking process. This system permits one to obtain the maximum pressure that the original braking system is able to apply on the wheels. Electronic components are needed to regulate this pressure as required by the computer. To this end, two electronic components are included. One is used to regulate the pressure between 0 and the maximum value, and the other to transmit this pressure from the pump to the wheels. In order to regulate the flow of the pressure, an electro-proportional pilot is installed with a nominal pressure between 12 and 250 bars. The control voltage varies between 0 and 10 volts. The electro-proportional pilot yields a non-null minimum pressure, and hence will always exert some small pressure on the wheels. The second element, a spool directional valve, is used to resolve this problem. It is normally open, and is only closed when the proportional pilot is actuated.

These two elements cause delays that cannot be disregarded if good behaviour of the system is desired. At the first sampling period after brake actuation is requested, a signal is sent simultaneously to both valves, and the actual delay corresponds to that of the slower element – the spool directional valve whose switching time is about 30 ms. For subsequent sampling periods, the spool directional valve is already closed and the delay corresponds only to that of the electro-proportional pilot, being even in the worst case at most 10 ms.

Following the design of the hydraulic and electronic components, the system needs to be plugged into the existing car braking system. To this end, a shuttle valve is installed to form the junction between the two systems. This valve permits flow from either of two inlet ports to a common outlet. A free-floating metal ball shuttles back-and-forth according to the relative pressure at the two inlets. Flow from the higher pressure inlet through the valve moves the ball to close the opposite inlet. This valve is thus responsible for the switching between the two braking systems. The model selected was the Hawe Hydraulic WV 6-S. It was chosen because the smallness of the flow through a braking system permits one to select the valve of least diameter which also has the smallest floating ball, thus minimizing the switching time. The valve is mounted so that the ball under gravity maintains the standard braking system open when the electro-hydraulic system is switched off.

The shuttle valve introduces a delay associated with the movement of the metal ball between the two inlets. The delay time calculated for the selected model was less than 1 ms for the minimum pressure of 10 bars.

The connection between the shuttle valve and the electro-hydraulic braking system is through the output of the spool directional valve which is connected to one of the inputs of the shuttle valve.

Figure 1 shows the design scheme of the braking system. The Citroën C3 Pluriel includes a safety system based on a duplicated braking signal. Therefore, two shuttle valves are used to switch between the conventional and the electro-hydraulic braking systems. The outputs of the two shuttle valves are connected to the ABS inputs. Finally, the ABS performs the distribution of the braking.

Figure 2 shows the shuttle valves assembled in the car. One of the goals was to maintain the original brake circuit unchanged. For this reason, the shuttle valves are installed as closely as possible to the ABS. One can see in the figure the two inputs of each shuttle valve. The lower input is connected to the automatic electro-hydraulic braking system, and the upper input to the original system.

The system described is designed to operate built into the AUTOPIA control system which has a sampling period of 200 ms. The design constraints of the braking system were that it should not introduce significant delays. The greatest delay appears on initiation of the automatic brake, and is the sum of the shuttle valve and the spool directional valve delays, the result being 31 ms. In the following sampling periods, there only exist the delays in the electro-proportional pilot, with values less than 10 ms.

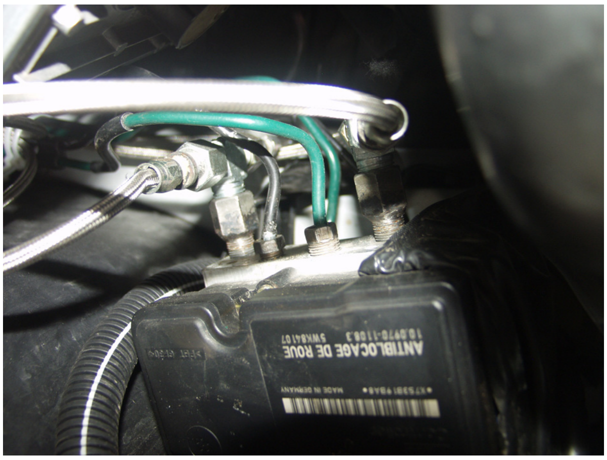

Figure 2. Locations of the shuttle valves.

The automatic system operates as follows. It is turned on by means of a manual switch installed in the dashboard. The dc motor is started by means of a relay that is activated when the switch is turned on. As long as the spool directional valve is open, a 10-bar pressure appears through the electro-proportional pilot and the flow is driven back to the tank. When the spool directional valve is closed, the pressure is applied to the shuttle valves and pushes their metal balls to the upper position to allow the brake fluid to circulate towards the brake shoes. From this moment onwards, the braking can be regulated by means of the electro-proportional pilot.

3. IMPLEMENTATION OF THE BRAKING SYSTEM

After constructing the braking system, we needed to decide on a place within the car in which to place it. The choice was to install the system under the trunk in the place reserved for the spare wheel. The compact design allows the use of this location where the pump is protected against collisions, and damage that may be caused by the driver is avoided. The spare wheel is now located at the same place under the chassis.

The pump dc motor is connected to a 12-volt auxiliary battery. This battery is fixed to the chassis by means of an elastic strap, and can be recharged with a socket in the lateral wall of the car that is directly connected to the car battery.

The auxiliary battery feeds another device as well as the dc motor. A CAN bus module is used to control the spool directional valve and the electro-proportional pilot by means of an on-board PC. This module consists of a 6-ampere relay output that is used to feed the spool directional valve, and a computer controlled analogue output that is connected to the electro-proportional pilot. The CAN module voltage supply is connected to the battery through the dc motor's accessible terminals so that it can be switched on by the same manual switch and at the same time as the dc motor.

Finally, the pump includes two outputs. One is divided into two and connected to the shuttle valves. The other is installed to measure the pressure with a manometer. The manual switch installed in the dashboard activates a relay that connects the power supply to the dc motor. A DIN rail is used to fix the CAN bus module and the relay. Figure 3 shows the distribution of each element under the trunk.

Several problems had to be solved. Initially, the fluid tank of the pump was closed by means of a vent plug, and the system worked well. But when the car was stationary, the brake fluid passed little by little from the original brake fluid tank of the car into the fluid tank of the pump. This was due to the fundamental hydrostatics: the place where we had put the pump was lower than the fluid brake tank of the car. Therefore, the brake fluid passed through the shuttle valves and the tank overflowed through the vent plug. The solution to this problem was to fill the tank to the limit and use an impervious plug to avoid overflow. This posed a new problem: when the pump was disconnected, there remained a small pressure in the circuit. This pressure increased and exerted a force on the brake shoes, and eventually the car became permanently braked. The solution adopted was to communicate the two tanks by means of a tube. A perforation was made in the impervious plug to allow a tube to be inserted into the tank of the pump. Another perforation in the vent plug of the original tank was made to communicate the two tanks. In that way, the necessary air vent for the pump was supplied by the original tank. The tank of the pump was filled to the limit, and the overflow produced returned to the circuit by means of the tube. The tube installed in the pump can be seen in Figure 3.

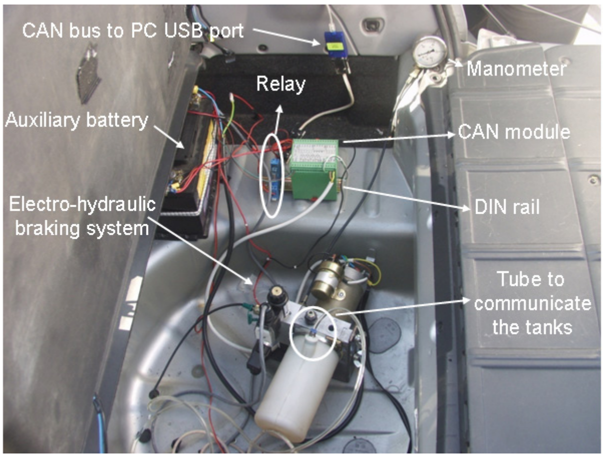

Figure 3. Location of the electro-hydraulic braking system.

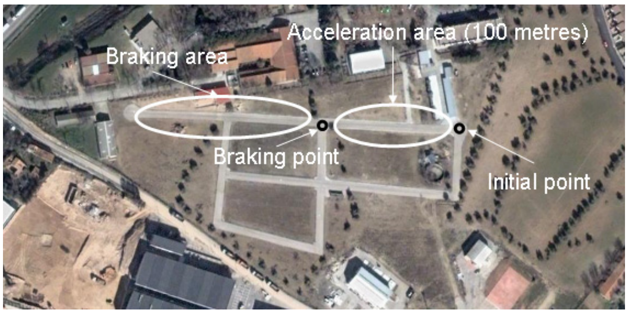

Figure 4. Private driving circuit at the IAI facilities.

4. BRAKING SYSTEM TEST

The system was implemented in a Citroën C3 Pluriel car. Several tests were performed to evaluate its behaviour in different situations, with very good results.

Figure 4 is a map of the private driving circuit at the IAI facilities. This circuit represents an inner-city area, with a combination of straight road segments, curves, and 90° intersections. The longest straight-road segment was used to carry out the tests since their main purpose was to observe the behaviour of the new braking system.

At each end of this stretch there are traffic roundabouts, and the car is initially located at one of them. The car is accelerated until the braking point to a speed of 46 kilometres per hour. The distance covered is around one hundred metres. During this time, the car is driven automatically, and the speed reference is introduced by means of software commands.

When the car reaches the braking point (Figure 4), a new speed reference of zero kilometres per hour is assigned. From this moment on, only friction forces are acting on the car, and the braking force can be evaluated.

First, manual tests were performed to determine the car's response to braking (Figure 5). The plots show the variation of speed with time along the road. The car accelerates during the first 13 seconds in automatic mode. The changes in slope in this interval are due to the automatic gearbox. Then the acceleration is stopped so that different responses can be studied. The top plot of the figure corresponds to no braking force being applied, and shows a slow decrease in speed. At around second 24, a change in slope can be observed that is due to the reduction in the gearbox. The middle plot shows the speed reduction when the human driver executes "soft" braking. In this case, around fifty metres are needed to stop the car. The idea is to try to identify habitual driver action while the driver is attentive to traffic. The bottom plot illustrates a case of "hard" braking, the idea being to identify an unexpected incident on the road requiring hard braking.

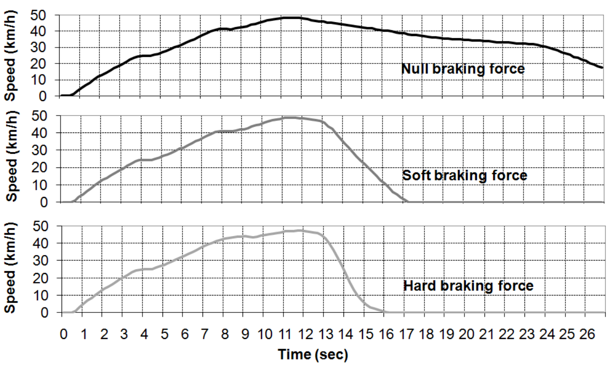

Figure 5. Manual braking tests.

Figure 6 shows the results of automatic braking with different tests carried out in order to compare their results with those of the manual response shown in Figure 5. As in the previous tests, the first part of each trial was done in automatic mode. The experiments were carried out by activating the electro-proportional pilot at different sets of values.

The electro-hydraulic pump is limited to 160 bars, and when it is working at this pressure the electro-proportional pilot is totally open (100%). Figure 7 shows the experimentally determined relationship between the opening percentage of the electro-proportional pilot and the pressure supplied by the pump. One observes that the relationship between the two variables is close to linear. The system designed thus exerts a pressure on the wheels that is linearly related to the control variable which is generated with an analogue output whose value ranges from 0 to 10 volts.

The pressure percentages, i.e., openings of the electro-proportional pilot, used in the tests were the following: 10%, corresponding to very soft braking; 20%, with a response similar to that of the manual soft braking but with a more uniform decrease in speed; 30%, where the car's behaviour is comparable to that of the manual hard braking; and finally 40%, corresponding to very hard braking to simulate an emergency stop. The braking in this last case is stronger that what a human driver would consider "hard" braking. Values greater than 40% were not used because they were considered uncomfortable for passengers.

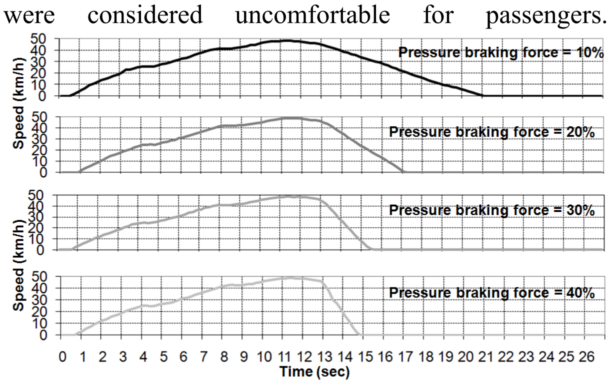

Figure 6. Automatic braking tests.

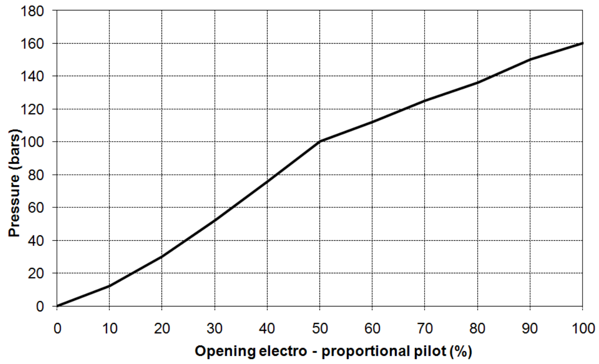

Figure 7. Relationship between the electro-proportional pilot and the pressure.

The results showed the electro-hydraulic braking system to present good behaviour, and even to have a better response than the manual system thanks to the linearization of the decrease in speed due to the constant braking reference.

5. AUTOMATIC CONTROL OF BRAKING

After the implementation and testing of the system, the following step was to incorporate it into the automatic vehicle. The AUTOPIA project's Citröen C3 Pluriel was already controlled longitudinally and laterally, but only the accelerator was used to control the speed so that the behaviour was still not sufficiently satisfactory.

Optimal longitudinal control of the vehicle requires cooperation between throttle and brake pedal. The AUTOPIA group had already implemented a braking system in two Citroën Berlingo vans in which the brake pedal was controlled by means of a motor that moved the pedal via a pulley. Since this method was too error-prone, the present novel way of controlling the brake was developed. However, the fuzzy-logic based controllers used in the Citroën Berlingo vans (Naranjo, 2006) were easily transferred to the Citroën C3 Pluriel because they yield normalized output values between 0 and 1, where 0 means no braking at all and 1 maximum pull.

The automatic system's behaviour shown in Figure 6 allows one to evaluate the braking response to different target values and match it with that of the human driver (Figure 5). Thus, the upper limit of the fuzzy controller was set to 40% of the maximum pressure of the pump.

Figure 8 shows the data of an automatic driving experiment around the private circuit at the IAI facility. The curves in the circuit force the changes in speed. The upper plot shows the comparison between the real speed and the target speed for 100 seconds, and the lower plot the output values of the brake and throttle fuzzy controllers. One observes that the brake signal is greatest when a large decrease in speed is requested. The variations in speed shown in the plot when the target speed is reached were small, about ±2.5 km/h, and imperceptible to the car's occupants.

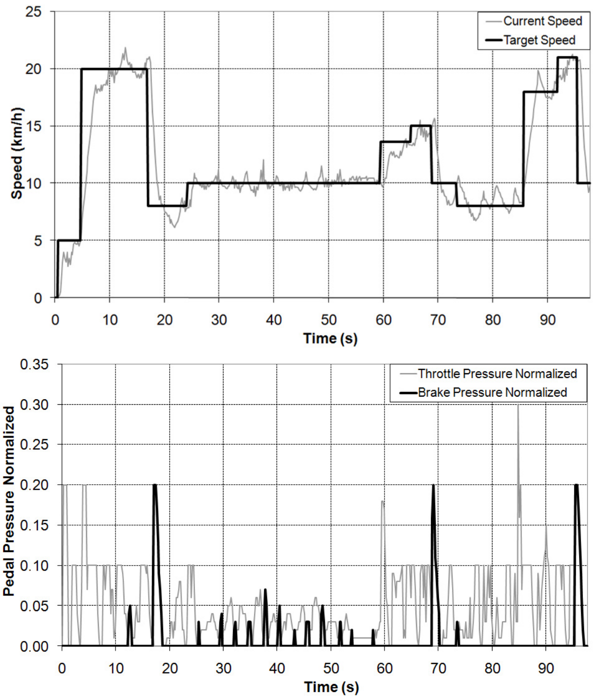

Figure 8. Targets for accelerator and brake on a track.

6. CONCLUSIONS

This paper has described the design and implementation of an electro-hydraulic braking system. A pump governed by means of three valves was designed to perform the control. One of these valves was used to limit the pressure, another to allow or avoid pressure circulation, and the third was an electro-proportional pilot to control the pressure of the brake fluid.

Some problems arose associated with the brake fluid pressure. They were resolved using a tube to communicate the tank of the pump and the car's brake fluid tank. A CAN bus module was used to perform the control of the system by means of software commands, and a relay connected to a manual switch in the dashboard was implemented to start the system.

Various tests of the designed system were carried out to verify its correct operation, yielding good results. Experimental trials were conducted to determine how the system behaves in imitating driver actions in different situations. The automatic system was shown to achieve linear reductions in speed in stopping the car –

one of the objectives in providing comfortable and safe braking.

The electro-hydraulic braking system was installed in the AUTOPIA automatic control car, and the experiments performed showed the behaviour to be good, with good speed control, and good subjective rating of the system by the car's passengers.

The results strongly suggest that an automatic collision-avoidance system can be used if an electro-hydraulic braking system is allowed to work at 100% of its strength. This would thus offer a possible solution for the reduction of car accidents on roads as a complement to obstacle detection systems.

ACKNOWLEDGEMENT– This work was carried out with the support of TRANSITO (TRA2008-06602-C03-01) project from Plan Nacional, GUIADE (P 9/08) project from Ministerio de Fomento and MARTA project (CENIT-20072006).

REFERENCES

Bu F., Tan H. (2007). Pneumatic Brake Control for Precision Stopping of Heavy-Duty Vehicles. *IEEE Trans. on Control System Technology* **15, 1**, 53-64.

Celentano G., Iervolino R., Porreca S., Fontana V. (2003). Car Brake System Modeling for Longitudinal Control Design. *IEEE Conference on Control Applications – Proceedings*; **1** 25-30.

Collado J.M., Hilario C., de la Escalera A., Armingol J.M (2004). Model Based Vehicle Detection for Intelligent Vehicles. *IEEE Intelligent Vehicles Symposium* 572-577.

Cummings P., Grossman D.C (2007). Antilock Brakes and the Risk of Driver Injury in a Crash: A Case-Control Study. *Accident Analysis &Prevention* **39**, 995-10.

Gerdes J.C., Hedrick J.K (1997). Vehicle Speed and Spacing Control Via Coordinated Throttle and Brake Actuation. *Control Eng. Practice* **5, 11**, 1607-1614.

Hong D., Yoon P., Kang H., Hwang I., Huh K (2006). Wheel Slip Control Systems Utilizing the Estimated Tire Force. *Proceedings of the 2006 American Control Conference* 5873-5878.

Jung S. P., Jun K. J, Park T. WYoon., J. H. (2008). Development Of The Brake System Design Program For A Vehicle, *International Journal of Automotive Technology* **9, 1,** 45-51.

Kang Y., Hedrick J. K. (2004). Emergency Braking Control Of A Platoon Using String Stable Controller. *International Journal of Automotive Technology*; **5, 2,** 89-94.

Kim H., Dickerson J., Kosko B (1996). Fuzzy Throttle and Brake Control for Platoons of Smart Cars. *Fuzzy Sets and Systems* **84**, 209-234.

Li Z., Wang K., Li L., Wang F (2006). A Review on Vision-Based Pedestrian Detection for Intelligent Vehicles. *IEEE International Conference on Vehicular Electronics and Safety* 57-62.

Liang H., Chong K., No T., Yi S (2003). Vehicle Longitudinal Brake Control Using Variable Parameter Sliding Control. *Control Engineering Practice* **11**, 403-411.

Lignon S., Sinou J-J., Jézéquel L (2006). Stability analysis and μ-synthesis control of brake systems. *Journal of Sound and Vibration* 1073-1087.

Maciuca D., Hedrick J.K (1997). Nonsmooth Dynamic Surface Control of Non-Lipschitz Nonlinear Systems with Application to Brake Control. *Proceedings of the 1997 IEEE International Conference on Control Applications* 711-716.

Maciuca D., Hedrick J.K (1998). Nonsmooth Estimation and Adaptative Control with Application to Automotive Brake Torque. *Proceedings of the American Control Conference* 2253-2257.

Naranjo J.E., González C., García R., de Pedro T (2006). ACC+Stop&go maneuvers with throttle and brake fuzzy control. *IEEE Trans. on Intelligent Transportation Systems* **7,2**, 213-225.

Naranjo J.E., González C., García R., de Pedro T., Haber, R.E (2005). Power-steering control architecture for automatic driving. *IEEE Trans. on Intelligent Transportation Systems* **6, 4,** 406-415.

Park E.J., Stoikov D., Falcao L., Suleman A (2006). A performance Evaluation of an Automotive Magnetorheological Brake Design with a Sliding Mode Controller. *Mechatronics* **16**, 405-416.

Petersen A., Barrett R., Morrison S. (2006). Driver-Training and Emergency Brake Performance in Cars with Antilock Braking Systems. *Safety Science* **44**, 905-917.

Ryu J. H., Kim C. S., Lee S. H., Lee M. H. (2007) H_∞ Lateral Control of an Autonomous Vehicle using the RTK-DGPS. *International Journal of Automotive Technology* **8, 5,** 583-591.

Song B., Hedrick J. K (2004). Design and Experimental Implementation of Longitudinal Control for Automated Transit Buses. *Proceeding of the 2004 American Control Conference* 2751-2756.

Song G., Jiang M., Zhao G (2006). The Research of an Intelligent Braking Control System. *7th IEEE International Conference on Computer Aided Industrial Design and Conceptual Design* .

Song J (2005). Performance Evaluation of a Hybrid Electric Brake System with a Sliding Mode Controller. *Mechatronics* **15**, 339-358.

Wang F., Herget C., Zeng D (2005). Guest Editorial Developing and Improving Transportation Systems: The Structure and Operation of IEEE Intelligent

Transportation System Society. *IEEE Trans. on Intelligent Transportation System*, **6, 3**, 261-264.

Wang J., Schroedl S., Mezger K., Ortloff R., Joos A., Passegger T (2005). "Lane Keeping Based on Location Technology". *IEEE Trans. on Intelligent Transportation Systems* **6,3,** 351-356.

World Health Organization (2004). World Report on Road Traffic Injury Prevention.

Yi J., Alvarez L., Horowitz R (2002). Adaptative Emergency Braking Control with Underestimation of Friction Coefficient. *IEEE Trans. on Control Systems Technology* **10, 3**, 381-392.