Cyber™ Tyre for Vehicle Active Safety

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SUMMARY. The automotive industry and their suppliers will have to face increasing demands in term of fuel economy and safety in the next years and decades. Consistent improvements of vehicle safety could be obtained if accurate information of the interactions between road and tires could be extracted and transmitted to the vehicle in real time: new control logics can be defined and implemented to better utilize the new available information. The paper describes the two main directions of the research: both in the field of features extraction from sensors applied on the inner liner of a tire and their possible utilization to improve the present vehicle control systems. This activity has implied the realization of some facilities to easily implement and test new algorithms, such as hardware in the loop test bench of the ABS and ESP.

1 INTRODUCTION

Chassis active systems are generally designed to support the driver to prevent accidents and at the same time increase vehicle dynamics performance. The design of active safety systems for passenger cars dates back to the eighties and it involved brakes, suspensions, steer and transmission. Due to the object of safety, the former applications regarded firstly the longitudinal dynamics improving acting, in particular, the vehicle stability through a more effective braking (ABS) and Traction Control (TC) systems. In nineties the Electronic Stability Control (ESC, ESP, VDC, IVD, DSC) added a significant increasing to the active safety acting, essentially, on brakes and engine torque to stabilize the vehicle in limit handling situations through controlling the yaw motion and, recently, the sideslip angle. Other chassis control systems act e.g. on roll bar (ARC), air spring, steering system (AFS), transmissions (AMT, DCT) with the object of safety and vehicle dynamics performance. Nowadays it seems that the performance obtainable using a stand-alone current chassis control system joined almost its target performance depending on the sensors actually available to support their control strategy. Usually an active chassis control strategy is based on estimation of fundamental characteristics quantities on the vehicle dynamics like, e.g., sideslip angle, slip, tire-road friction and forces applied. The performance could significantly increase if more detailed information could be real-time measured directly by new sensors economically sustainable. Many activities concerning the chassis control systems integration are in developing to overcome the fundamental problem of the lack of more information directly related to the vehicle dynamics. Nevertheless, it is well-known that the availability of either sideslip angle measurement or, especially, the forces applied in the contact between tire and road can increase significantly the chassis active system currently performed.

The state-of-the-art briefly formerly described is the base of the research activity proposed by the Authors to present the co-operation among Pirelli Tyre, Politecnico di Milano and Politecnico di Torino devoted to a new instrumented tyre, called Cyber^{TM} Tyre, capable to measure during rolling the forces applied to the pavement and to predict the available friction. The activities concerning the Cyber^{TM} Tyre regard a number of methodological and technological aspects and involve research methodologies concerning, e.g., virtual analysis, identification, Hardware-in-the-loop (HIL) experimental test bench, road test, space available for sensors, weight, durability.

2 THE CYBER^{TM} TYRE CONCEPT

The Cyber^{TM} Tyre is devoted to real-time predict the forces exchanged between tyre and road and the friction available. To carry out the estimation, the tyre is instrumented with a node, in the following called sensor node, including many components. The main sensor node components are acceleration sensors, a Digital Signal Processor (DSP) to generate raw data and optimized to save energy, an antenna to wireless transmit raw data and an energy scavenger system to supply the energy required by the node. The Cyber^{TM} Tyre concept is not limited to the sensor node but includes components and algorithms required to interface the data coming from tyre with the vehicle. Consequently, the Cyber^{TM} Tyre concept includes an antenna, installed in the wheel arch, used as receiver of the data transmitted by the antenna in the sensor node, an algorithm (Feature Extraction Unit - FEU) to extract the desired feature and the interface to publish the identified quantities predicted in the Controller Area Network (CAN) of the vehicle. The data published in the CAN are finally available for chassis control system and generally for Advanced Driver Assistance Systems (ADAS) like, e.g., Adaptive Cruise Control (ACC). The real-time estimation data carried out by the FEU is very promising to improve the control strategy of chassis control systems devoted to active safety. All the elements formerly resumed, both components and algorithms, are originally conceived for the Cyber^{TM} Tyre. A large part of the components currently under testing are patented or in process to be patented ([4],[5],[6]).

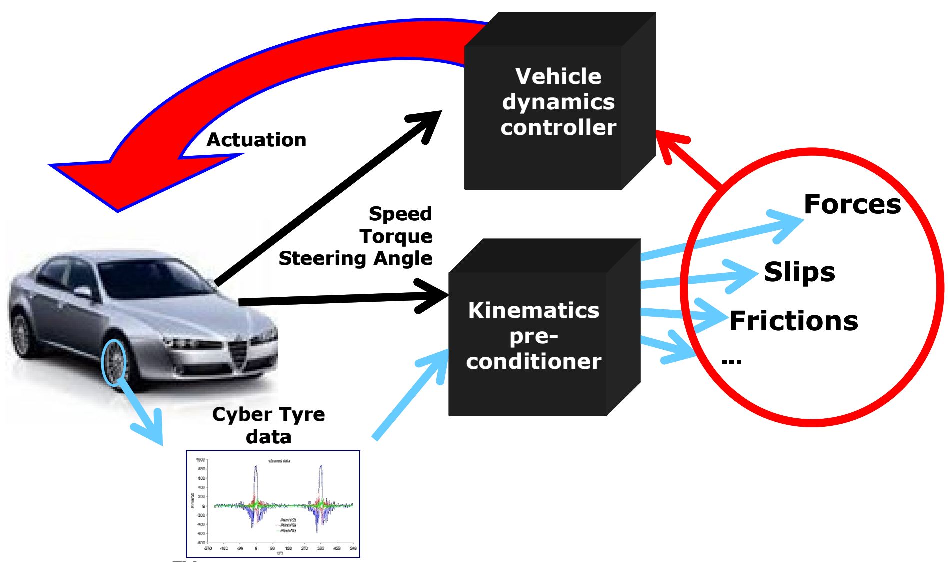


Figure 1: Cyber^{TM} Tyre qualitative relationships with a vehicle dynamics controller

Figure 1 presents a qualitative scheme concerning the relationships existing among the identified quantities extracted on the base of the real-time measurements carried on by Cyber^{TM} Tyre and vehicle dynamics controller parameters tuning.

3 FEATURES EXTRACTION

The raw data generated by the sensor node are used by an algorithm conceived to real-time predict global quantities of special interest, like the forces exchanged in the tyre-road contact patch, named *features* ([3]). Figure 2 shows, as an example, the measured circumferential acceleration during straight track running; it can be seen that the entering and the exiting of the accelerometer in the contact patch is evidenced by peaks having opposite sign.

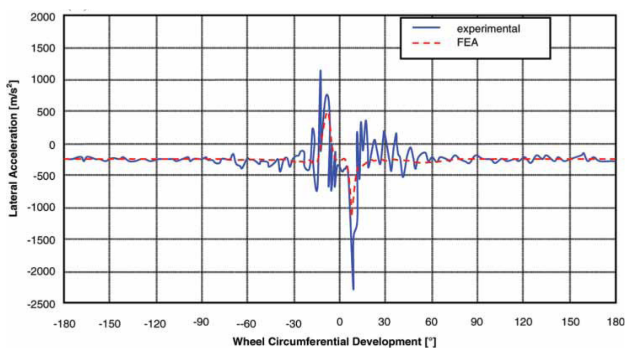


Figure 2: Example of the time history of the circumferential acceleration measured by the sensor node

Several algorithms ([4],[5],[6]) were developed in order to process the raw data transmitted by the sensor node and to turn them into features. Each algorithm was developed through two main steps:

- As first, several indoor test sessions were carried out with MTS Flat Trac; this machine allows to test a Cyber^{TM} Tyre under controlled working conditions: parameters like vertical load, slippage, slip angle and camber angle can be imposed by a control system. During this phase it has been possible to analyze the response of Cyber^{TM} Tyre to each individual input; joining these information with the results of simplified tire models, correlations were identified between the raw data and the features.
- As second step, outdoor tests were performed with a passenger car equipped with 4 Cyber^{TM} Tyres. This phase was required to check the validity of the proposed algorithms considering the normal operative conditions experienced by a tire and the introduction of external disturbances like the road irregularity.

Figure 3a reports the results of the first stage: on the basis of a numerical model of a vehicle, a sweep sine test was reproduced on MTS Flat Trac; the comparison between the normal contact force predicted by the testing machine and the corresponding value obtained through the Cyber^{TM} Tyre is shown. Figure 3b is referred to an output of the second development step previously described: the comparison between the estimated global longitudinal force (sum of the longitudinal forces measured by all four Cyber^{TM} Tyres, also called “estimated”) and the product of the measured longitudinal acceleration times the vehicle mass during a series of acceleration and braking manoeuvres (also called “measured”). A very good correlation is found thus evidencing the reliability of the developed algorithms.

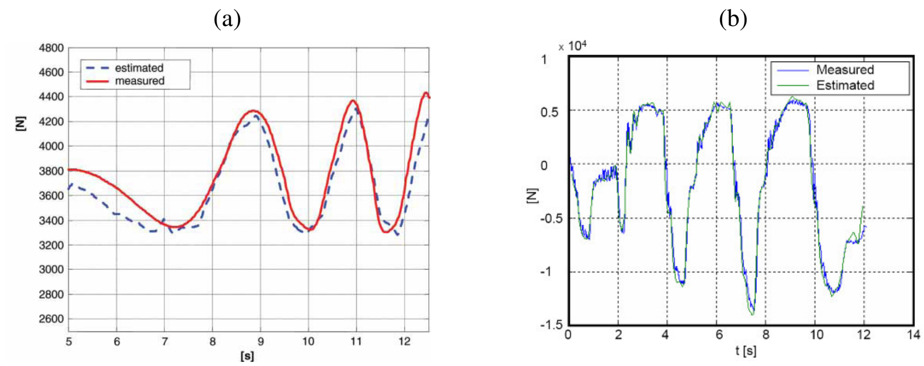


Figure 3: Indoor test: comparison between the measured and the estimated normal load (a); outdoor test: comparison between the measured and estimated longitudinal force (b).

4 METHODOLOGICAL OVERVIEW

The research activities on the Cyber™ Tyre system require a multidisciplinary approach, involving different teams skilled in mechanics, electronics, computer science, telecommunications, manufacturing, materials. A so complex project strongly profited by the know-how available thanks to the co-operation among Pirelli Tyre, Politecnico di Milano and Politecnico di Torino. Each one of the partner shared its specific know-how and test rigs to support the project. The partnership agreement involved at the moment not less than fifty researchers belonging to Industry and University. To support the co-operation, a Laboratory for Cyber™ Tyre was specifically founded at Politecnico di Torino to gather both the researchers mainly involved in the project aspects requiring know-how integration and the experimental equipment useful for more team with different skill. For example, the diagnosis activity on Cyber™ Tyre, managed by a computer science research team, benefits from the availability of Hardware-in-the-Loop (HIL) test benches conceived by vehicle dynamics team to investigate the potentialities of Cyber™ Tyre on chassis control systems. Similarly, vehicles equipped as Mobile Laboratory were on purpose bought and equipped by vehicle dynamics teams of both the Politecnico to be available for the number of testing by the other teams with different skill (electronics, telecommunications, etc.).
In the following, some of the methodologies adopted to face the problems related to vehicle dynamics aspects of the project, will be shortly described.

4.1 *Virtual analysis*

Virtual analysis is generally considered a fundamental methodology to investigate how a new system can determine benefits and to support the research and development process of the system itself. In the present activity, virtual analysis regarded all the aspects of the projects, showing strong analogies about the instruments adopted in areas devoted to aims apparently far. For example, the typical FEA are commonly used both for technological evaluation and for transmitting antenna emissivity. To investigate relationships between Cyber™ Tyre and vehicle dynamics, a typical example of virtual analysis is the mathematical model carried out to simulate the dynamic behaviour of the vehicle used to experimentally test the new system. The vehicle dynamics simulator carried out is a typical fourteen degree of freedom, including some of the main elastic and damper characteristics of the vehicle.

The peculiarity of the mathematical model developed was the capability to be directly moved in a real-time simulator for tests based on HIL test bench. Figure 4 shows an example concerning the input and output of the vehicle dynamics model as structured to be used in a real-time application. In the example the inputs are the braking pressures applied to the calipers and to the Tandem Master Cylinder (TMC), coming either from a test bench or from the vehicle equipped as mobile laboratory. Moreover, fundamental inputs are the data available in the CAN network, concerning a number of signals coming from the various Electronic Control Unit (ECU) currently largely active in a vehicle. Similarly, the output present in the example are devoted to reconstruct at the input of an ECU, in the current case the Electronic Stability Control (ESC) one, all the signal required to correctly work. According to this example, is reasonable that the vehicle dynamics model has to be tailored to be used not only for simulation but especially for the need to be used also for real-time integration with chassis control systems like ESC.

The vehicle dynamics simulator was positively validated using experimental road tests carried out by Pirelli's professional drivers according to the ISO regulations currently applied to measure vehicle performance longitudinal and lateral, in steady-state (ramp steer manoeuvre), transient (step steer) an forced steady-state (sweep steer).

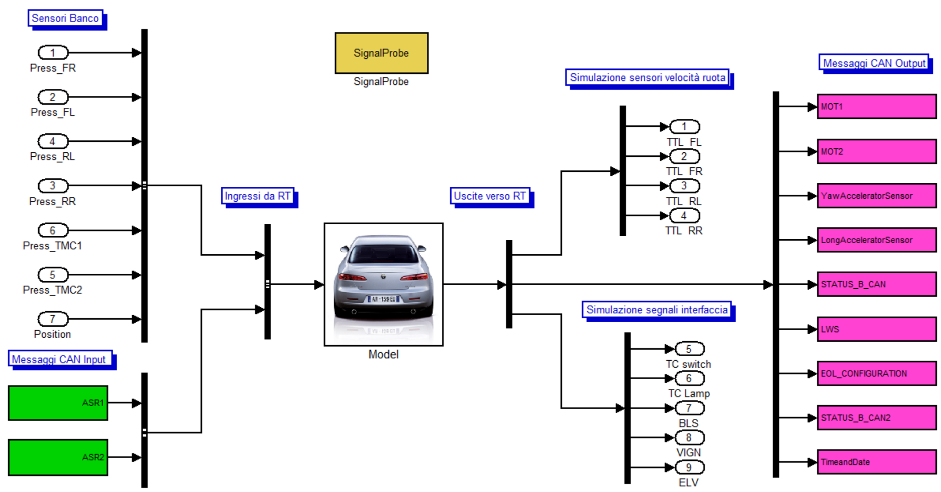


Figure 4: Scheme of vehicle dynamics model I/O for real-time applications

4.2 *Hardware-in-the-Loop (HIL) test bench*

Hardware-In-the-Loop (HIL) is a testing methodologies currently used to support design and validation of chassis control systems. The main idea of an HIL is to study the influence of a part of a system on the overall vehicle dynamics interfacing the physical subsystem under investigation with the remaining part, including the signal network, simulated in real-time ([8]). For example, to study the active braking system physically available in the HIL is necessary to carry out the Controller Area Network (CAN) exactly as in the vehicle to prevent fail signals. HIL is a logic link between virtual model and road test, permitting to analyse performance of an innovative chassis control system saving time and cost in comparison to the traditional experimental techniques, usually based on road tests.

Generating the same set of signals as an ECU normally receives when is operating in the vehicle, it is possible to duplicate with the HIL test bench how the ECU works when subjected to driver inputs and vehicle and road operating conditions. In such way it is possible to accurately and objectively investigate how a chassis control system works in normal production operating conditions.

An ABS/ESC HIL test bench was built to support the development of new control strategies using the quantities (i.e. contact forces) identifies through Cyber^{TM} Tyre. It consists of a whole brake system, integrated through specific interface with a vehicle model running in real-time on a specific platform. Commercial ABS control strategies performance can be measured carrying out a number of manoeuvres standardised or not like, for example, panic brake, manoeuvres in μ-split, brake manoeuvres with an abrupt change of the friction coefficient between tyres and ground. Similarly all the signals required to activate a commercial ESC can be generated: steering wheel angle, body yaw rate, body lateral acceleration, engine control, etc. Some of them are transmitted by CAN. Typical handling manoeuvres are used to test the ESC: step steer, double step steer, ramp steer, etc.

ABS/ESC HIL test bench considers the overall hardware of a whole braking system. Figure 5 presents a photo of the braking systems test bench. Figure 6 presents an example of Electro-Hydraulic Control Unit (EHCU) modified to directly control the ABS electrovalves according to a new control strategy including Cyber^{TM} Tyre signals. All the braking system components tested are common production hardware, belonging exactly to a defined vehicle setup, in order to obtain realistic results. Booster input rod is hydraulically actuated. The vehicle model gave origin to a very good accordance with road tests results.

Figure 5: ABS/ESC HIL test bench

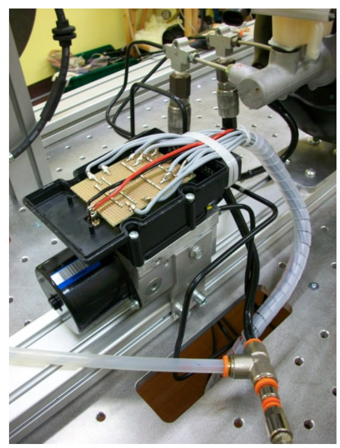


Figure 6: ABS EHCU directly controlled according to an innovative control strategy

Figure 7 describes the HIL data flow among real-time simulator and physical components. To integrate the vehicle dynamics with the ABS/ESC EHCU are required both specific hardware and software platform for HIL system and electronic cards on purpose carried out. To duplicate on HIL test bench the operating conditions to which the chassis control system will be subjected in the vehicle, the EHCU needs to receive many digital signals as it should receive in the real vehicle. A lack or a not exactly identical set of signals determine the impossibility to duplicate at HIL the normal operating of work of the EHCU. In this way it is possible to compare the performance obtained with a new control logic and a normal production one, maintaining during testing with HIL exactly the same vehicle and the same electrohydraulic braking system.

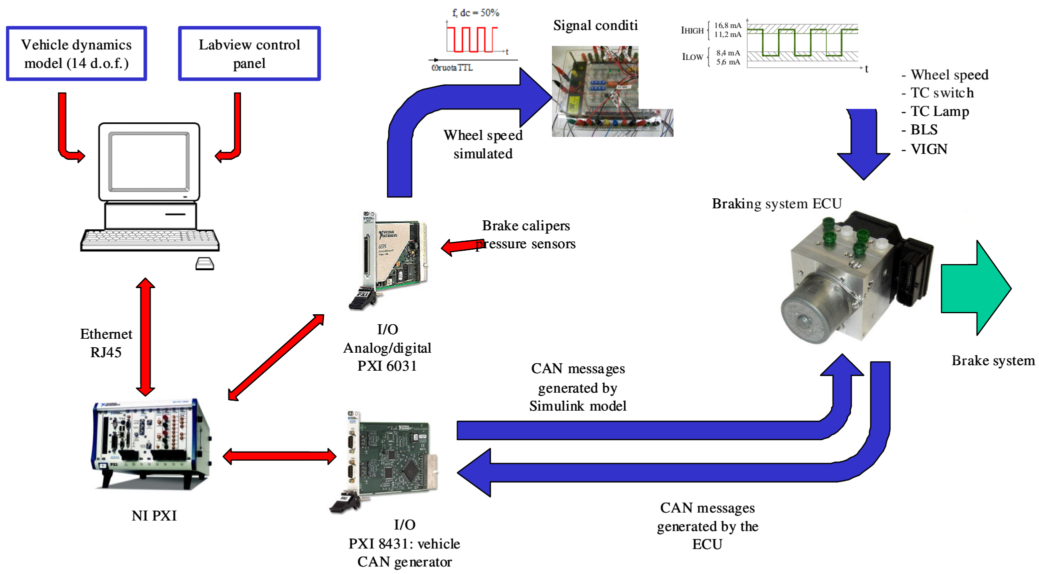


Figure 7: HIL data flows among real-time simulator and physical components

The HIL test bench results were experimentally validated through road tests.

Figure 8, as an example of validation, presents a comparison between longitudinal acceleration measured with a vehicle equipped as Mobile Laboratory (LAM) and HIL test bench during passive braking. Figure 9 shows a stopping distance comparison between LAM and HIL test bench during the same passive braking. Similarly, Figure 10 resumes a comparison between longitudinal acceleration measured with LAM and HIL test bench during active braking and Figure 11 shows a stopping distance comparison between the experimental vehicle and the HIL test bench during active braking.

4.3 *Development of new control strategies*

New control strategies are being developed considering the availability of new information concerning the vehicle dynamics provided by Cyber^{TM} Tyre. As first step an analysis has been carried out considering possible enhancements of the performance of the EBD system. Electronic brake force distribution (EBD) allows to automatically vary the brake pressure on each wheel according to road conditions, vehicle speed and vertical tire-road contact force in order to maximize the total braking force and avoid macro-slippages. In fact, the most important parameter to determine the optimal brake pressure on each wheel is the wheel load ([8]): the higher the load, the higher the brake pressure (with equal tire-road friction conditions). Cyber^{TM} Tyres are able to provide wheel loads and, therefore, they can significantly improve the performances of traditional EBD logics. To quantify the influence of Cyber^{TM} Tyres system on EBD control logics, a brake step is applied to a 14 degrees of freedom vehicle model that is running on a straight track at

150km/h. Results in terms of brake distances were obtained considering the vehicle equipped with fixed distributor, with EBD and with EBD+Cyber™. Table 1 summarizes the numerical results, showing the differences in terms of braking distances obtained with the three vehicles; as well known the vehicle equipped with EBD is able to obtain shorter braking distances with respect to a vehicle mounting a fixed distributor: with a payload of +30% the braking distances are reduced up to 3.5%.

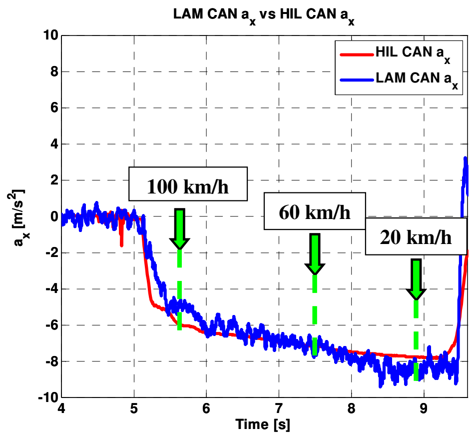
	EBD vs Fixed Brake Distributor	EBD+Cyber™ Tyre vs Fixed Brake Distributor	EBD+Cyber™ Tyre vs EBD
Light payload	-0.59%	-2.65%	-3.15%
Rear payload +15%	-2.15%	-5.12%	-4.70%
Rear payload +30%	-3.15%	-6.17%	-4.86%
Payload +15%	-2.30%	-4.09%	-2.94%
Payload +15%	-3.46%	-4.95%	-2.55%

Table 1 differences of the brake distances [%] obtained comparing the performances of fixed distributor, EBD and EBD+Cyber**™** Tyre

The vehicle equipped with EBD+Cyber™ Tyres that provide information about the vertical load acting on each wheel, can significantly improve this result: the reduction of the brake distance reaches values of 5-6% with a payload of 30% with respect to the vehicle using a fixed distributor. Considering the comparison of the performances offered by the EBD alone and by the same system coupled with Cyber™ Tyres, the expected reduction of brake distances reaches 5% when a rear payload is present.

5 CONCLUSIONS

The paper presented an example concerning how a co-operation among Pirelli Tyre, Politecnico di Milano and Politecnico di Torino can integrate efficiently their respective know-how, especially as methodologies and laboratories, to do research in challenging fields. In particular, the example concerned a research devoted to a new generation of tyre equipped with a sensor node to real-time predict the main magnitudes typical of the tire-road interaction. The results till now obtained demonstrated that the research can significantly benefit from the co-operation. The paper exemplified such results referring to features extraction from sensors applied on the inner liner of a tire and their possible utilization to improve the present vehicle control systems. Some methodologies carried out to support the research activities were shortly described.



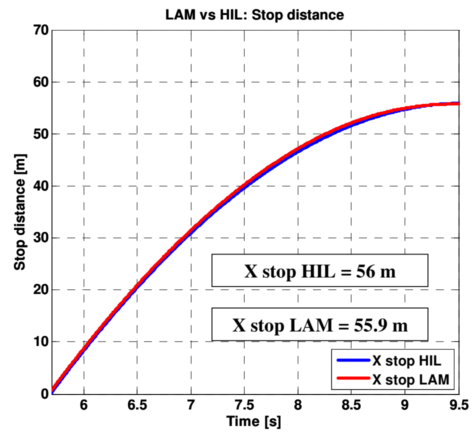
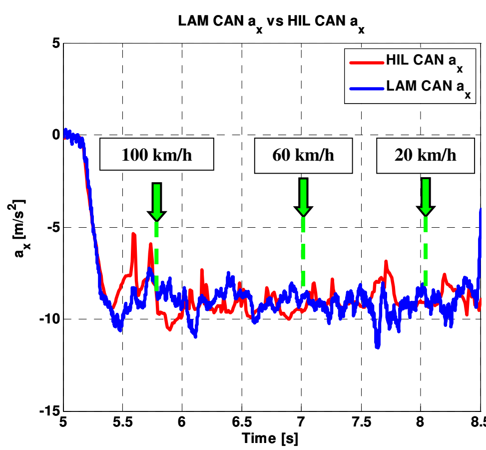


Figure 8: comparison between longitudinal acceleration experimental vehicle (LAM) and HIL test bench during passive braking

Figure 9: Stopping distance comparison between experimental vehicle (LAM) and HIL test bench during passive braking



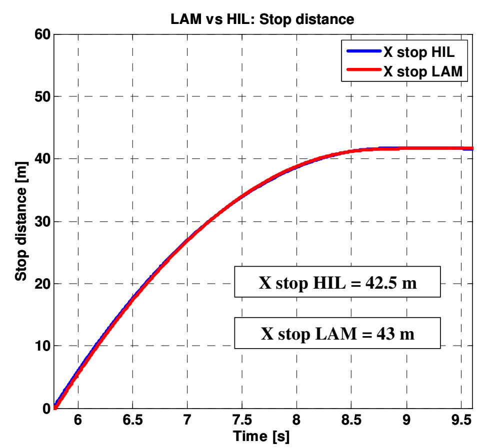


Figure 10: Comparison between longitudinal acceleration experimental vehicle (LAM) and HIL test bench during active braking

Figure 11: Stopping distance comparison between experimental vehicle (LAM) and HIL test bench during active braking

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