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DYNAMIC TIRE PRESSURE CONTROL SYSTEM – ANALYSIS OF THE EFFECT ON LONGITUDINAL VEHICLE DYNAMICS AND FUEL CONSUMPTION

Höpping, Kristian[1]*; Augsburg, Klaus*[1]

[1] TU Ilmenau, Department of Mechanical Engineering, Automotive Engineering Group

ABSTRACT

The choice of the optimal tire pressure is always a conflict of aims. The tire pressure has a significant influence on safety, comfort and environmental behavior. The development of a dynamic *Tire Pressure Control System* (*TPCS*) can reduce the conflict of minimal rolling resistance and maximal traction.

The first part of the paper discusses the evaluation of tire pressure influence on fuel consumption and vehicle dynamics. The relevant study has been performed using the numerical simulation tool *IPG CarMaker*. For this purpose a vehicle model was created and validated. To analyze the influence of the tire pressure on tire characteristics a tire model was developed using *MATLAB Simulink*. Tire parameters were analyzed on a tire test rig and implemented in the tire model. Using synthetic and real driving cycles as well as driving manoevres, the simulation results confirm a high potential in reducing fuel consumption and simultaneously increasing traction forces by adapting the optimal tire pressure. Moreover, control strategies were developed to adapt the optimal tire pressure depending on the actual driving conditions. The strategies were implemented in *MATLAB Simulink* and connected to the *IPG CarMaker* simulation.

Since the potential of a *TPCS* is particularly high for light-duty commercial vehicles (with different loading conditions, a high curb weight, and available space for pneumatic system), a Mercedes Sprinter was equipped as a test vehicle. A pneumatic system was developed that allows changing the inflation pressure of each tire independently and highly dynamically with a rate of 2.5 bar per second. In addition to the powerful hardware, rule based control strategies were implemented to reduce fuel consumption and improve vehicle dynamics. To demonstrate function and efficiency of the *TCPS* and to validate the developed simulation model, driving tests were performed on a test area.

Results of numeric and experimental analyses point out, that an intelligent and dynamic *Tire Pressure Control System* has a significant potential to increase safety and efficiency for future mobility.

Index Terms – tire inflation pressure, tire pressure control system, stopping distance

1. INTRODUCTION

The tire inflation pressure has a significant influence on vehicle safety, comfort, tire wear and rolling resistance losses. As example of influence of tire pressure on vehicle safety it is advisably to review changes of braking distance of a vehicle. Based on the results of investigation provided by Goodyear the braking distance (vehicle speed is 45 mph or around 72 km/h) goes 8% down on wet macadam and 10% down on wet concrete when tire pressure is changed from 17 to 35 psi (about 1.2 to 2.4 bar). [1] NHTSA testing shows that stopping distance (vehicle speed is 60 mph or around 97 km/h) goes 3% down (from 15 to 30 psi) on wet concrete, 1,5% down (from 15 to 35 psi) on dry concrete, 2% down (from 30 to 35 psi) on wet asphalt, and 3% down (from 30 to 35 psi) on dry asphalt. [1] Hadrys et. al. measured, that the stopping distance beginning at an initial velocity of 60 km/h can change from 22 meters to 24.6 meters on dry road and from 25.4 m to about 29 meters on wet road when changing the tire pressure from 2 bar to 3 bar at the front axle. [2] Marshek et.al. found out that an ABS emergency braking on a dry road is reduced at low and high tire inflation pressures and is optimal at the tire inflation pressure recommended by the vehicle manufacturer. The absolute value of this effect depends on the investigated car. [8]

In addition, tire inflation pressure influences the fuel consumption of a vehicle. A reduction in rolling resistance of 5 to 7 % produces a 1 % increase in fuel economy. [3] According to data provided by Goodyear an under-inflation of 8 psi (about 0.5 bar) results in a 3.3 % decrease in MPG [4]. Another analysis shows that 30 % loss in rolling resistance (or an under-inflation of 1 bar) decreases fuel consumption by 5%. [5,9] Deflated tires (0.6 bar under recommended tire pressure) can increase fuel consumption up to 4%. [6] In addition, a reduction of tire wear can also increase economy of a vehicle. Tire lifespan can be reduced by 45 % for 0.6 bar under-inflated tires. [6]

The optimal tire pressure also depends on mass of carrying cargo that is necessary to take into account for determination of optimal tire pressure level for improvement of fuel performance. In addition, 10 to 20 kPa loses of tire pressure is equivalent of additional 70 kg of transporting cargo. [7]

An incorrect tire pressure is the reason of a large number of road accidents. The biggest part of fatal vehicle crashes (about 36 %) that have happened in 2009 in the USA falls at damaged and smooth tires. [10] According to the German Federal Office of Statistics 985 accidents with personal injury happened in 2011 in Germany are referable to tire problems. [22] An efficient way to improve vehicle safety, vehicle performance and reduce rolling resistance losses and tire wear lies in the proper maintenance of tire pressure during vehicle driving. For this purposes all new light passenger vehicles in the U.S. from 2006 and all new vehicle models in the European Union from 2012 have to be equipped with tire pressure monitoring systems (TPMS). The market proposes a variety of tire pressure monitoring systems. In addition to the safety aspect, TPMS can reduce fuel or energy consumption of about 2.5 to 3%. Subsequently, the CO_2 emissions could be reduced by about 9.6 million tons per year (calculated for EU-15 countries). [11]

However, modern TPMS have a very limited functionality. For example, they can inform the driver about current tire pressure levels, or they can warn when a tire have to be inflated. Therefore tire pressure maintenance systems were introduced. The analysis of research sources shows that the first applications of central pneumatic systems allowing the tire pressure adjustment while driving have appeared more than five decades ago, first of all for off-road, military and agricultural ground vehicles. However, in the majority of known constructions, the driver must initialize a pressure change. More advanced designs with an automatic inflation are proposed in a series of patents and technical solutions of *Dana Coproration, Knorr-Bremse, Arvin Meritor, TIREMAAX* and several other manufacturers. In 2011, for example, Goodyear's *Air Maintenance Technology (AMT)* was presented. It will enable tires to remain inflated at one optimal pressure level without any external pumps or electronics. Unfortunately, the pressure cannot be changed (due to the driving situation). [16]

Most of the known tire pressure control or maintenance systems are for off-road, military and agricultural ground vehicles. They change the pressure slowly and usually have to be initialized by the driver. An essential improvement of the *Tire Pressure Control Systems (TPCS)* functions can be achieved through an intelligent controlled and highly dynamic *TPCS*. This concept is the kernel of the research project ADTYRE that is being performed by the consortium of academic and industrial partners from Germany, Hungary and Lithuania. The presented paper introduces the effect that can be achieved by different longitudinal vehicle maneuvers using a *TPCS*.

2. SIMULATION MODEL

To analyze the effect of a *Tire Pressure Control System* on vehicle dynamics and fuel consumption, in addition to AVL CRUISE primarily the simulations are performed using the numerical simulation tool *IPG CarMaker* in co-simulation with *MATLAB Simulink*. The *TPCS* variants, which are under development in the ADTYRE project, concern different vehicle models. Within the framework of the presented paper, the simulations are carried out with the light-duty commercial vehicle Mercedes Sprinter. The detailed vehicle model is developed and validated with a number of measurements. An excerpt of the parameters is given in Table 1.

Vehicle type	Mercedes Sprinter W906 509 CDI (2006 model)
Overall weight (incl. *TPCS*, driver, front-seat passenger)	2944 kg
Static wheel-load distribution (front/rear)	51 % / 49 %
Engine	2.148 ccm Diesel engine (65 kW at 3800 rpm, 220 Nm at 1600 rpm)
Tyre type	Goodyear Cargo G26
Tire dimension	205/75 R16 C
Length	7040 mm
Width	1990 mm
Track width	1708 mm
Wheel base	4325 mm
Height of the center of gravity	915 mm

Table 1: Specification of test vehicle Mercedes Sprinter

In addition to the detailed model of the hydraulic brake system, an algorithm of an anti-lock brake system by Burckhardt [20] is implemented using *MATLAB Stateflow*.

By modeling the tires of the test vehicle Mercedes Sprinter, the empirical Magic Formula tire model by Pacejka has been used. Although there exist a number of physical models as the brush model, SWIFT model or LuGre model [13, 17, 23], the MF model is still very accurate with a reasonable calculation time and it is possible to identify all parameters within an appropriate time. The Pacejka parameters were calculated in accordance to the measurement of the Mercedes Sprinter tires at the internal drum test bench at the Karlsruhe Institute of Technology. Longitudinal force vs. slip was analyzed on dry, slightly wet road (0.5 mm water depth) and wet road (2 mm water depth) for three different tire pressures: 2.5; 3.75 and 5.0 bar. Examples of the longitudinal tire characteristics are given in Figure 1.

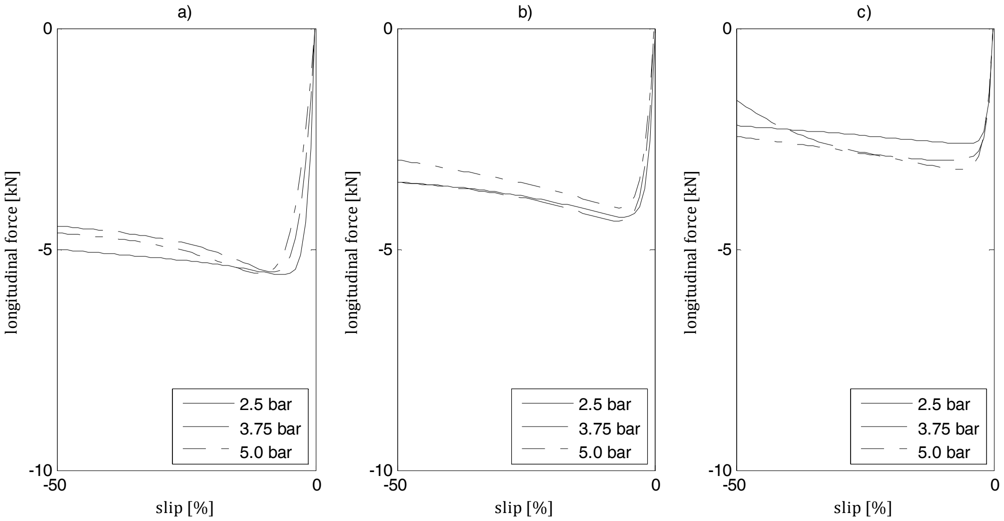

Figure 1: tire characteristics depending on tire pressure (F_Z = 6500 N)
a) dry road b) 0,5 mm water depth c) 2,0 mm water depth

The stationary longitudinal tire characteristics of the analyzed tires confirm the qualitative expectations. As shown in [12, 24] a clear correlation between tire inflation pressure and longitudinal tire stiffness as well as the maximum friction coefficient can be seen in these measurements. Because of the reinforced tire structure (with a load index of 110), the difference of the maximum friction coefficient on dry roads is not very significant. On wet asphalt the dependencies are changing. A higher inflation pressure results in a higher maximum traction force. This phenomenon can be described with aquaplaning effects and correlates with the findings in publication [25].

In addition, the rolling resistance of the named tires was measured at the external drum test bench with a diameter of 2 meters at the same pressure levels and the speeds 50, 90 and 120 km/h. After running-in to reach the steady-state condition, each measurement was taken for 15 minutes. The rolling resistance includes flexing and air resistance. The results of the mean value for the 3 speeds according to ISO 8767 are shown in figure 2.

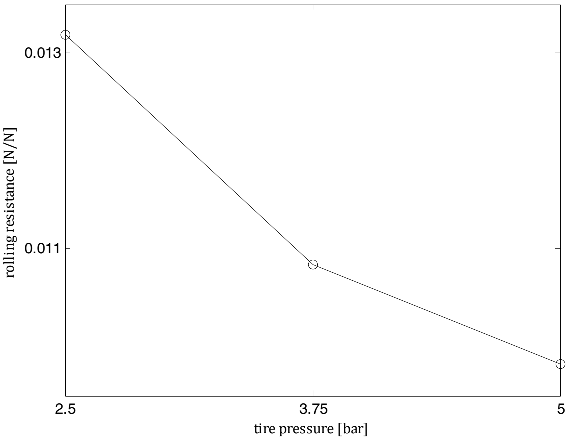

Figure 2: rolling resistance depending on tire pressure (F_Z = 6500 N)

To analyze the effect of a *TPCS* on vehicle dynamics, the tire inflation pressure needs to be changed during a simulation maneuver, i.e. the tire model has to take the pressure into account. Several studies are going in the same direction and propose advancements of tire friction models with the tire pressure parameter. For instance, variations of LuGre [14] as well as Magic Tire Formula and SWIFT models [26] are known where the computation of wheel slip and longitudinal tire forces takes into account the tire pressure variations. Unfortunately, these models are only valid in a small range of inflation pressure or not validated for many types of tires. Hence, an own *MATLAB Simulink* tire model is developed on the basis of the parameterized MF model. In addition to the basic (slip) calculations, look-up tables were used, which allow an interpolation between the different pressures depended characteristics. Moreover, a simple first-order transient tire model was implemented.

3. SIMULATION RESULTS

To evaluate the vehicle dynamics by alterable tire pressures, a number of simulation manoeuvers have been performed. This paper will concentrate on studying the fuel consumption, climbing performance and braking distance. Using the climbing performance manoeuver implemented in *AVL CRUISE* the maximal inclination can be calculated depending on the maximal traction coefficient. The results, presented in figure 3, point out a significant influence of the tire inflation pressure. Especially on wet roads, the maximal inclination can vary from 19.0 to 23.7 %.

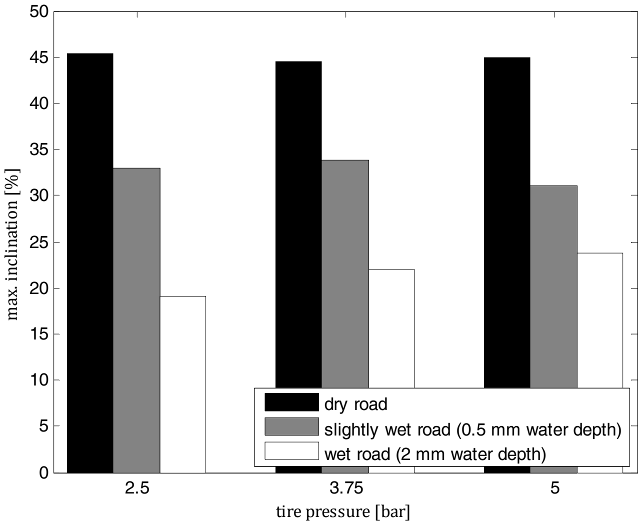

Figure 3: climbing performance depending on tire pressure

The calculated series of full stop braking manoeuvers using *IPG CarMaker* in co-simulation with *MATLAB Simulink* are based on standard ISO 21994. Therefore, the mean deceleration is analyzed between 70 km/h and 5 km/h and the normalized stopping distance from an initial speed of 100 km/h is calculated (cp. chapter 4). The results are presented in figure 4. Their analysis allows to draw a number of conclusions, which are of special relevance for the further design of the *TPCS*. An increase of tire pressure in all wheels influences the braking distance especially on wet roads essentially. It was observed that a higher inflation pressure (1.25 bar higher than suggested standard pressure of 3.75 bar) decreases the braking distance by 1.7 meters on wet roads (2 mm water depth), whereas reducing the pressure by 1.25 bar increases the braking distance by 15 meters. Reducing the tire inflation pressure from 5.0 to 3.75 bar decreases the stopping distance by 4.9 meters on slightly wet roads (0.5 mm water depth). On dry roads the effect is marginal.

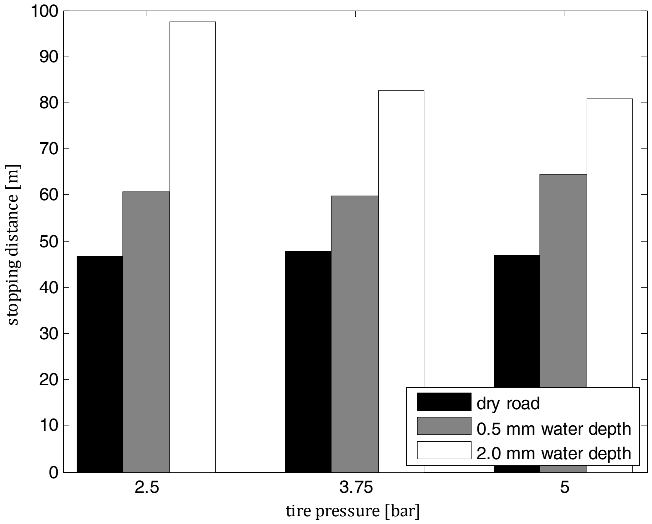

Figure 4: calculated stopping distance from 100 km/h depending on tire pressure

To calculate fuel consumption different driving cycles were analyzed:

1) Constant drive with 100 km/h
2) Ilmenau real driving cycle (the circuit covers a 33 km long combination of motorway, urban and suburban roads in and around Ilmenau)
3) New European Driving Cycle (NEDC)
4) Federal Test Procedure (FTP-75)

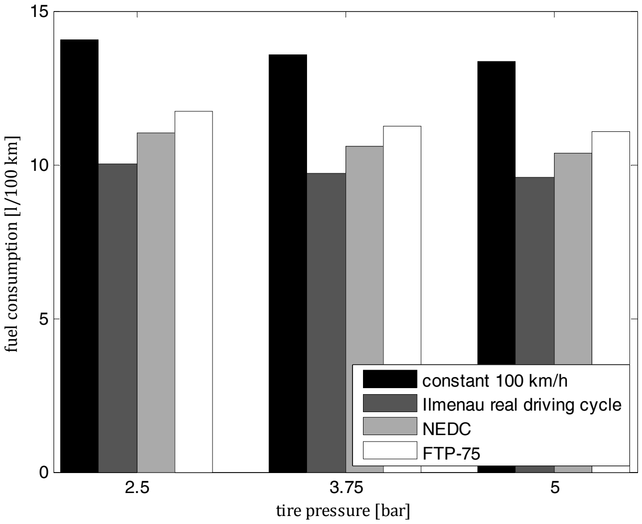

Figure 5: calculated fuel consumption depending on tire pressure

The determined fuel consumptions depending on the inflation pressure are presented in figure 5. The results for the NEDC e.g. show that a higher inflation pressure (1.25 bar higher than suggested inflation pressure of 3.75 bar) decreases the fuel consumption by 1.9 percent, whereas reducing the pressure by 1.25 bar to 2.5 bar increases the fuel consumption by 4.2 percent. Focusing on the carbon dioxide emissions, i.e. increasing the inflation pressure from 3.75 bar to 5.0 bar could reduce the emissions by 5.3 g/km, whereas decreasing the inflation pressure to 2.5 bar could increase the emissions by 11.9 g/km.

4. FUNCTIONAL VALIDATION

To validate the simulation results, real driving tests were performed at the proving ground and airfield Alkersleben. Full stop braking tests were carried out on a dry high-µ road and a white painted wet low-µ road based on standard ISO 21994. To measure the braking distance the GPS based Racelogic VBox 3i was used. In addition to velocity, longitudinal acceleration and braking distance, wheel speeds were logged using the vehicle CAN Bus. Moreover, the brake pedal was equipped with a pedal force sensor and the brake pressure at the front left brake and front right brake were measured using pressure transducers. Preparing the braking tests, the vehicle was conditioned and brake discs and tire temperatures were acquired. According to ISO 21994, the brake discs did not exceed 120 °C before starting a brake procedure. To guarantee a full stop braking with ABS control, the brake pedal was actuated very fast and the minimum pedal force was 500 N. To reduce the random error of the driving tests, at least 10 braking tests – 5 in each direction - were performed from an initial speed of 80 km/h for each tire pressure. To evaluate the grip performance the mean fully developed deceleration (MFDD) was used. On the high-µ road, the braking distance between 70 km/h and 5 km/h was analyzed, on the low-µ road the braking distance between 70 km/h and 35 km/h (because of the limited length of the low-µ area) was analyzed. Consequently, the results are more repeatable and accurate. Pressure built up time and rock back period can be neglected. Accuracy of a speed to speed test with the VBox is about ±5 cm. [18, 19]. To reduce possible errors and deviations, the highest and the lowest stopping distance were not analyzed. Out of 8 measurements a mean value of the stopping distance was calculated. Using this value, the mean deceleration a_i and the normalized stopping distance s_{norm} can be calculated [21]:

$$a_i = \frac{v_{70}^2 - v_5^2}{2 \cdot s_i} \tag{1}$$

$$s_{norm} = \frac{v_{norm}^2}{2 \cdot a_i} \tag{2}$$

Figure 6 shows the results of the braking tests on high-µ and low-µ road for a normalized speed of 100 km/h. Although brake disc and tire tread temperatures as well as pedal brake force and ambient conditions (wind speed did not exceed 5 m/s and ambient temperature was between 20°C and 24°C) are in the same range for all measurements, there are differences in stopping distance within the series of measurement with the same tire pressure. Different friction coefficients or water depths at different tracks and a slightly different reaction of the ABS controller could be an explanation for this phenomenon. The measured values and the mean value of stopping distance are represented in figure 6. The results confirm the calculated outcomes. The difference in stopping distance on dry asphalt vanishes within the measurement error. On the white painted wet low-µ road a higher potential to reduce the braking distance by changing the inflation pressure occurs. The braking distance could be reduced by 4.38 meters when changing the tire pressure from 2.5 to 5.0 bar.

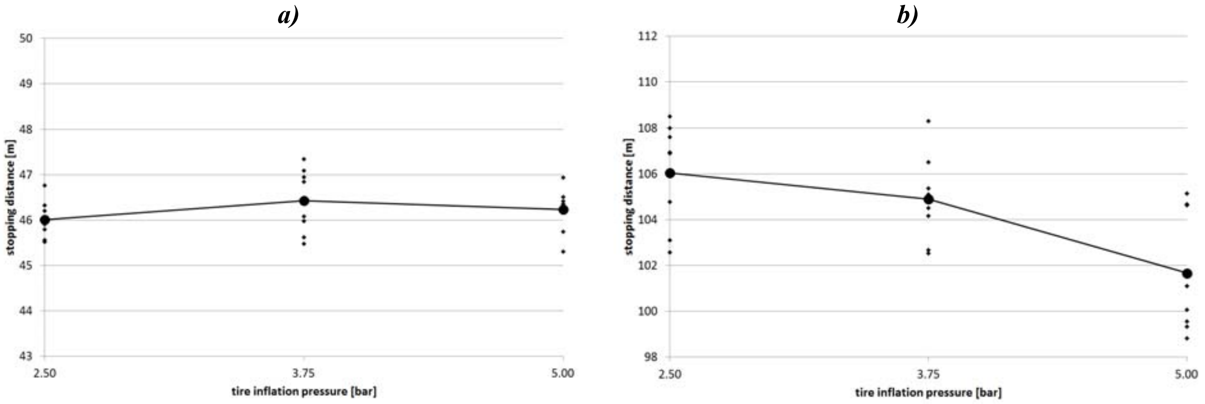

Figure 6: measured normalized stopping distance from 100 km/h depending on tire pressure
a) dry road b) wet road

To validate the fuel consumption simulation model, the consumed fuel of the Mercedes Sprinter at different tire inflation pressures was measured. Therefore, a Gregory Flowtronic S8005C was used. The system is suitable for Diesel, petrol and bio fuel. The measuring range is between 0.1 and 250 liters per hour. The accuracy is 0.5 % of the measured value.

5. TYRE PRESSURE CONTROL SYSTEM

As mentioned before, the optimal tire inflation pressure is not a constant value. It depends on driving manoeuver, vehicle load, road conditions etc. First, the effect of a *Tire Pressure Control System* is analyzed with the simulation tool *IPG CarMaker*. Therefore, an algorithm is developed to control the optimal inflation pressure. This rule-based algorithm for longitudinal vehicle dynamics has been implemented in the *IPG CarMaker* and *MATLAB* co-simulation model using *MATLAB Stateflow*. According to the driving condition, the optimal tire pressure is adopted. The basic strategy of the controller is to reduce rolling resistance by increasing tire inflation pressure at higher velocities and higher loads. Realizing an emergency braking, e.g. by identifying a high brake pedal force, a high brake pedal actuation velocity or an adequate value of an ACC sensor, the desired inflation pressure is changed to an optimal value. Based on a standard tire pressure of 3.75 bar, simulation results show that the stopping distance of the analyzed commercial vehicle equipped with a *TPCS* could be reduced by 2.2 percent on dry roads, 3.7 percent on wet roads (2 mm water depth) and 8.9 percent on slightly wet roads (0.5 mm water depth) assuming a deflation and inflation time of 1 second for a pressure difference of 2.5 bar. Based on the braking distance of under-inflated tires (2.5 bar), the difference in stopping distance can be up to 16 meters on wet roads.

Analyzing the energy efficiency of a *Tire Pressure Control System* is very complex. The efficiency depends on the additional weight of a *TPCS*, the energy consumption of a compressor and on the sophisticated operating strategy. Assuming an additional weight of 50 kg of a *TPCS*, not regarding a high consumption of a compressor and increasing the inflation pressure from 3.75 bar to 5.0 bar when the vehicle velocity exceeds 50 km/h, the carbon dioxide emissions of the NEDC can be reduced by approximately 2 g/km. Reducing the additional weight of a *TPCS* and optimizing the (predictive) operating strategy could improve the effect.

The first step by designing a test vehicle demonstrator with a *Tire Pressure Control System* is connected with the definition of reasonable time limits for dynamic tire inflation/deflation processes. The time limits have a strong relation to vehicle dynamics. It is supposed that an automatic change of tire pressure must be quite fast to influence longitudinal manoeuver, for instance, to reduce braking distance or rolling resistance on-the-fly. The useful tire pressure range of the test vehicle Mercedes Sprinter is defined between 2.5 and 5.0 bar. Since an emergency braking from 100 km/h (on dry roads) take approximately 3 seconds, the maximum allowable time of tire inflation or deflation within the appointed pressure range should be not more than 1.0 s. Using the simulation tool *LMS AMESim*, a layout of the pneumatic system is designed. Figure 7 introduces the system architecture proposed for the realization of *TPCS* functions. A full description of the system configuration is presented in [15]. After an optimization of the system, the developed and constructed pneumatic system is able to increase or decrease the tire pressure within a range of 2.5 bar to 5.0 bar within 1 second separately or simultaneously in all four wheels.

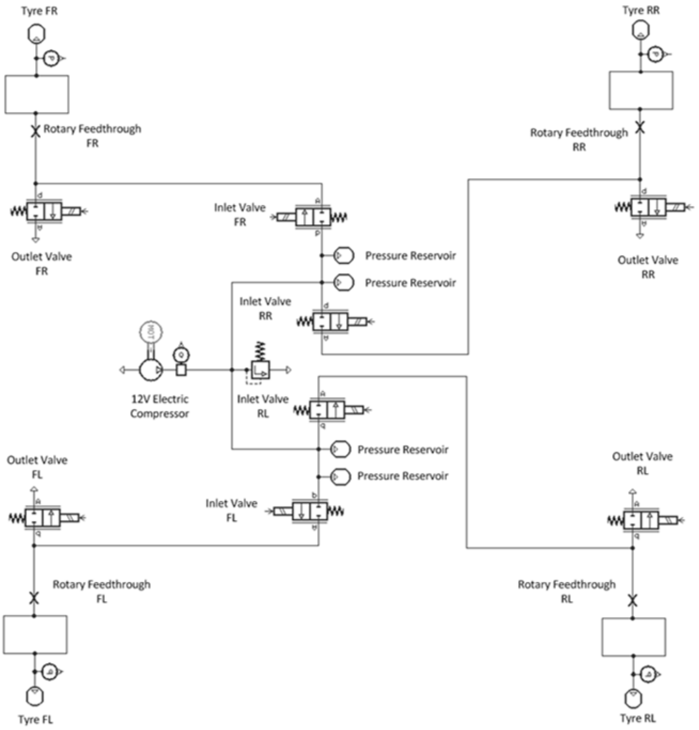

Figure 7: pneumatic layout of TPCS

Figure 8a) shows the realization on the test vehicle Mercedes Sprinter. Figure 8b) presents the design of the control and data acquisition system. The developed control algorithms (and used for simulation analyses) are now implemented on a computer using *MATLAB Simulink* with DAQ Toolbox. The computer is connected with different sensors and the vehicle CAN Bus using the *National Instruments* USB devices *NI 6361* and *NI 9862*. Essential for the *TPCS* are the *senTec PEDRA* wireless pressure sensors acquiring the inflation pressure with 10 Hz. The receiver allocates the signals via CAN Bus. The control valves to inflate or deflate the tires are connected with the digital output of the *NI USB-6361* Data Acquisition Box and can be controlled separately for each wheel.

Figure 8: a) test vehicle with TPCS b) communication layout of test vehicle with TPCS

To verify the functionality of the developed demonstrator, several experiments were carried out. The current work will further be concentrated on analyzing the stopping distance. Based on the experiments described in chapter 4, full stop braking maneuvers with a *Tire Pressure Control System* are investigated. Unlike to the very complex predictive algorithms used for the simulation analyses, the algorithms implemented in the test vehicle to determine the desired tire pressure are basically very simple. The standard inflation pressure is 3.75 bar. If the vehicle exceeds a certain velocity threshold, an inflation to 5.0 bar occurs. If an emergency brake situation is detected by recognizing a very fast brake pedal actuation and a brake pedal force of more than 300 N, the inflation pressure will be reduced to 2.5 bar on dry roads and increased to 5.0 bar on wet roads. To de- or inflate the tires rapidly, the 2-way valves are opened when a large control deviation occurs. To control the tire pressure precisely, a pulsed operation is activated when the control deviation is small. Figure 9 presents an example of a braking maneuver on a wet low-μ road. Beginning the experiment with a tire inflation pressure of around 3.75 bar, a critical situation is recognized by the *TPCS* and the inflation pressure is increased to 5.0 bar within approximately 0.5 seconds.

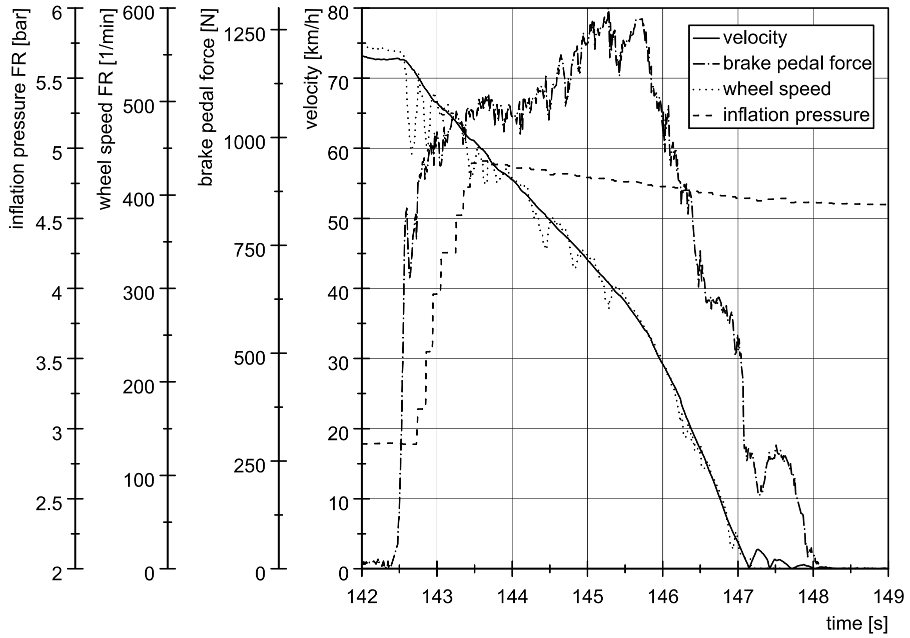

Figure 9: Example of a braking maneuver experiment

6. SUMMARY AND OUTLOOK

The simulation results and the real driving tests confirm a high potential of a highly dynamic *Tire Pressure Control System.* By adapting the tire pressure according to the driving condition, the rolling resistance and consequently the fuel consumption respectively the CO_2 emissions could be lowered. Simulation results show that the stopping distance from an initial speed of 100 km/h of a commercial vehicle equipped with a *TPCS* could be reduced by 2.2 percent on dry roads, 3.7 percent on wet roads and 8.9 percent on slightly wet roads assuming an initial tire pressure of 3.75 bar. Based on the braking distance of under-inflated tires (2.5 bar), the difference in stopping distance can be up to 16 meters on wet roads.

To validate the calculated results, a demonstrator test vehicle was developed and constructed. The described *Tire Pressure Control System* is able to change the tire inflation pressure within a range of 2.5 bar to 5 bar within 1 second according to the driving condition. The performed experiments confirm the results of the simulation and the high potential of a *TPCS.*

Analytical and experimental investigations carried out by the authors show that the effect with different tires can be even more enhanced. A more detailed investigation of the effect of tire inflation pressure on stationary and transient tire characteristics is part of a next paper of the authors.

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CONTACTS

Dipl.-Ing. K. Höpping kristian.hoepping@tu-ilmenau.de