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INVESTIGATION OF LATERAL DYNAMICS OF TRIPLE HYBRID HYDROGEN BUS

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Abstract. *The TriHyBus (abbreviation of the Triple Hybrid Hydrogen Bus) project comprises research and development, implementation and a test operation of a city bus with hybrid electric propulsion using hydrogen fuel cells. The mass distribution and the total bus mass are rather different from common buses. It is the reason of verifying the bus chassis strength and investigating the bus driving stability. In order to obtain a tool for dynamic analysis multibody models of the bus were created using the alaska simulation tool. The aim of the simulations with the verified TriHyBus multibody models is the calculation of time histories or frequency responses of kinematic and dynamic quantities giving information about the investigated properties of the vehicle at the selected operational situation. Verification of multibody models was performed on the basis of comparison of simulations results and results of experimental measurements focused on the field of lateral dynamics of the bus. Test drives focused on the TriHyBus driving stability (severe double lane-change manoeuvre and moose test) were performed with a real vehicle in November 2012. In comparison with the previous experimental measurements on the similar vehicles much more utilizable data were recorded for performing simulations of driving manoeuvres with multibody models and their verification. From the point of view of simulations with the TriHyBus multibody model the measured bus speed and bus trajectory were the quantities for defining input data of test drives. Selected quantities recorded during the test drives, viz. relative displacements of the air springs before the rear axle, roll and yaw angles, were monitored. On the basis of comparing the simulations results and the results of experimental measurements it is evident that a certain coincidence of results exists. Not completely perfect coincidence of the results is influenced mostly by the ignorance of the actual air pressure in air springs of the bus suspension. In the case of further possible test drives with the real TriHyBus it will be necessary to measure the pressure in air springs due to defining multibody models more precisely.*

1 INTRODUCTION

The TriHyBus (abbreviation of the Triple Hybrid Hydrogen Bus) project comprises research and development, implementation and a test operation of a city bus with a hybrid electric propulsion using hydrogen fuel cells. The mass distribution and the total bus mass are rather different from the common buses. It is the reason of verifying the bus chassis strength [1-3] and investigating the bus driving stability [4, 5]. In order to obtain a tool for dynamic analysis multibody models of the bus were created using the **alaska** software. The aim of the simulations with the verified TriHyBus multibody models is the calculation of time histories or frequency responses of kinematic and dynamic quantities giving information about the investigated properties of the vehicle at the selected operational situation.

Results of simulations of severe double lane-change manoeuvre according to ISO 3888-1 and a “moose” test (with the empty bus multibody model created in **alaska 2.3** simulation tool), which were performed with a real bus in a parking place near a swimming pool in Mělník (Czech Republic) in November 2012 [4, 5], are mentioned in this paper. Simulation results are compared with the evaluated records of experimental measurements. Pieces of knowledge following from comparison of results of experimental measurements and computer simulations are summarized.

Figure 1: TriHyBus at experimental tests in Mělník.

2 BASIC TECHNICAL DATA

The TriHyBus project comprises research, development, implementation and a test operation of a 12-meter city bus (see Figure 1) with a hybrid electric propulsion using hydrogen fuel cells. The prototype of the bus was manufactured by ŠKODA ELECTRIC Inc. using the Irisbus Citelis 12M bus chassis produced by Iveco Czech Republic, Inc. The 48-kW Proton Motor membrane fuel cell is used as a main power-source of the 120-kW electric traction motor. Additional 28-kWh traction accumulators and ultracapacitors are utilized when the bus accelerates or ascends, working together with the fuel cell, allowing energy recuperation while decelerating.

The TriHyBus driveability is desired to be comparable with the characteristics of standard buses [6]. However, the mass distribution and the total bus mass are rather different. It is the reason of verifying the bus chassis strength (connected with vertical dynamics) and investigating the bus stability (i.e. horizontal dynamics). Vertical dynamic properties of the real vehicle were experimentally investigated at testing drives on an artificial uneven test track created on a road near Neratovice (Czech Republic) railway station in March 2012 [7]. As it has been already stated horizontal dynamic properties were experimentally investigated in November 2012 [4, 5].

3 MULTIBODY MODELS IN BRIEF

In order to obtain a tool for dynamic analysis (e.g. [8]) several types of multibody models of an empty (14 tons weight) and a fully loaded (18 tons weight) hydrogen bus were created [9, 10].

The TriHyBus multibody models have been created using the **alaska** simulation tool [11] and on the basis of analytical derivation in the MATLAB system. Each model has its advantages and its drawbacks and can be used for different purposes.

The Irisbus Citelis 12M bus chassis is used only in the produced TriHyBus prototype. Chassis of some of the Neoplan (Germany) buses is planned to be used at further buses. As Iveco Czech Republic, Inc. is acquainted with this fact it is not interested in providing data about chassis of its own production. Verifying the bus chassis strength is only part of one of eight stages of the project solving (stages are mostly aimed at development of hydrogen technologies). Thus generally ignorance of data needed for modelling some chassis parts (especially shock absorbers force-velocity characteristics [1, 7]) in the bus multibody models does not endanger a successful solution of the TriHyBus project as a whole.

Due to the shorter computational time and relatively satisfactory results [1, 2, 5, 7] the basic multibody model of the TriHyBus (e.g. [10]; see Figure 2) created in the **alaska 2.3** simulation tool was chosen for the computer simulations. This multibody model is formed by 21 rigid bodies coupled by 24 kinematic joints. The number of degrees of freedom in kinematic joints is 39. The multibody model kinematic scheme is given in [9] or [10].

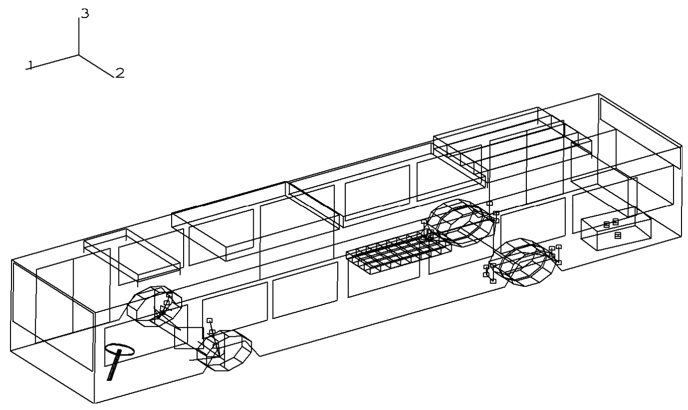

Figure 2: Visualization of the TriHyBus multibody model in **alaska 2.3** simulation tool.

The rigid bodies correspond to the bus individual structural parts and are defined by mass, centre of gravity coordinates and mass moments of inertia. Air springs and hydraulic shock absorbers in axles' suspension and bushings in the places of mounting certain bus structural parts are modelled by connecting the corresponding bodies by nonlinear spring-damper elements. The stationary tire model is used to describe the directional properties of the tires.

The TriHyBus multibody models were created especially on the basis of data (numerical data and technical documentation) provided by ŠKODA ELECTRIC Inc. Since producers of some constructional parts of the bus chassis had not been willing to provide data needed for the multibody models creation certain input data were derived or taken from the multibody models of the SOR C 12 intercity bus [12] and the ŠKODA 21 Tr low-floor trolleybus [13].

Characteristics of air springs (force in dependence on deflection) were determined on the basis of static loadings of axles derived from the data provided by Iveco Czech Republic, Inc. [9]. As it has been already stated, the biggest drawback of multibody models is the ignorance of real force-velocity characteristics of shock absorbers [1, 2, 7]. Force-velocity characteristics of the shock absorbers that were "proposed" as optimum by BRANO Inc., the shock absorbers producer, on the basis of technical data about the bus [5] are used in the TriHyBus multibody models.

Radial stiffness and radial damping properties of the wheels with tires suitable for this vehicle type (MICHELIN 275/70 R 22,5 XZU tire) were experimentally measured in the Dynamic Testing Laboratory ŠKODA RESEARCH Ltd. The evaluation of the measured quantities for the purpose of the multibody models creation is given e.g. in [14]. The tire radial characteristics identified at specified tire inflation pressure (and "with the weight of a 3 ton mass" – see [14]) are used in the multibody model.

4 TEST DRIVES AND THEIR SIMULATION

Five test drives out of twelve were simulated with the empty bus basic multibody model created in the **alaska** simulation tool: three times the severe lane change manoeuvre according to ISO 3888-1 and twice the "moose" test [5]. The test drives which were simulated were selected on the basis of experimental measurements results analysis. In this paper results of two simulated test drives are given.

The severe double lane-change manoeuvre according to ISO 3888-1 is a widespread testing method for a subjective evaluation of the dynamic properties of the road vehicles. The scheme of the test track, which must be run through, is in Figure 3. The overall track length in case of the double lane-change manoeuvre according to ISO 3888-1 is 125 m, the individual track sections width is dependent on the vehicle width.

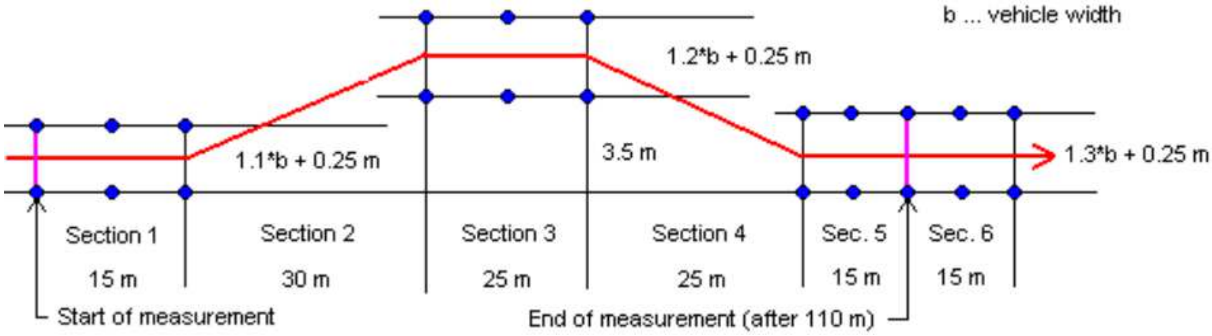

Figure 3: Scheme of the test track for the severe double lane-change manoeuvre according to ISO 3888-1 (scheme taken from [15]).

The "moose" test is the test used for determining the vehicle behaviour at severe lane change manoeuvre to avoid an unexpected obstacle. In Sweden this test has been used for many decades because the most frequent unexpected obstacle is a moose there. A collision with this even-toed ungulate is tragical for the travellers in most cases. The test name is thus derived from this animal. The track, which must be driven through during this test, is schematically drawn in Figure 4.

Both tests are performed on the smooth surface of a horizontal road. The vehicle must go at determined speed before entering the test section and after having driven through it must brake down. That is why the area, in which the test drives are performed, must be sufficiently long. During the tests maximum speed of driving through the test track without knocking down the cone outlining the track is evaluated. It is possible to evaluate if the maximum tested vehicle speed is sufficient on the basis of comparison with another vehicle of the similar type or on the basis of requirements of its potential operators.

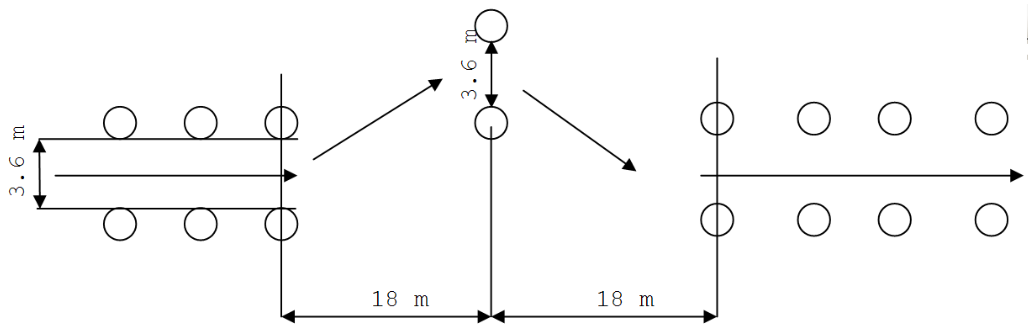

Figure 4: Scheme of the "moose" test track.

At experimental tests with the real TriHyBus the measured quantities were recorded at sampling frequency 400 Hz. Time histories of acceleration in various bus spots, time histories of relative displacements between the rear axle and the chassis frame (at the left air spring and at the right air spring), track courses, time histories of the bus speed and time histories of the bus angle around three mutually perpendicular axes [4] were the measured quantities among others. Comparing to previous experimental measurements on similar vehicles (e.g. [16, 17]) much more usable data were recorded in order to simulate driving manoeuvres with multibody models and their verification. Not only time histories of relative displacements between the rear axle and the chassis frame (and alternatively time histories of bus roll angle) but also track courses, time histories of bus speed and time histories of bus yaw angle were at disposal.

Lateral and longitudinal increases of the track trajectory were calculated using simple goniometric relations from the measured values of the track course and the time history of the yaw angle. Track trajectory was then determined by integrating those increases [4].

In the course of experimental measurements first the bus went along the test track at standard speed and then at maximum possible speed. In the case of the severe double lane-change manoeuvre the maximum achieved speed was influenced by the limited length of used road section. A driver went along the test track at maximum speed 45 km/h at the severe lane change manoeuvre and at maximum speed 40.5 km/h at the "moose" test. Test drives were sensationally very dynamic and the bus seemed to be stable [4].

From the point of view of the simulations with the TriHyBus multibody model the measured time histories of the bus speed and the calculated tracks trajectories were the essential quantities for defining input data of test drives.

The aim of the simulations with the verified TriHyBus multibody models is the calculation of time histories or frequency responses of kinematic and dynamic quantities giving information about the investigated properties of the vehicle at the selected operational situation. Selected quantities recorded during test drives, viz. time histories of relative deflections of the right air spring before the rear axle, time histories of relative deflections of the left air spring before the rear axle, time histories of roll angle around the longitudinal axis (around axis "**1**" – see Figure 2) and time histories of yaw angle around the vertical axis (around axis "**3**" – see Figure 2) were the monitored quantities – see Figures 5 to 10.

For the simulation of the test drives with the TriHyBus multibody model the driving approach using a so called "mean wheel" (according to Ackermann principle – e.g. [18]) was applied. The trajectories of a motion of the "mean wheel", i.e. of the fictitious wheel with the centre of the wheel trace in projection of the centre of the steered front axle to the road, were the tracks trajectories of the real bus. The “mean wheel” steering angle is determined on the basis of the tangent slope to the trajectory of the “mean wheel” motion in the given time and on the basis of the deviation of the “mean wheel” position from the trajectory in the given time. The weight of the influence of the deviation of the “mean wheel” position from the trajectory of motion in the given time is optional and thus the driver reaction time can be set. In dependence on the “mean wheel” steering angle the instantaneous steering angles of the wheels of the steered front axle (or its knuckle pins) are determined in the TriHyBus multibody models [16, 19, 20].

Simulation of each test drive starts in the moment in which, during the test drive, the real TriHyBus reaches the speed of 15 km/h and ends when the real TriHyBus speed is lower than 15 km/h. Monitoring the vehicle start and braking is not the test drives simulation purpose and, in addition, simulation of the start from zero speed should cause certain problems in the course of comparing the results (see [5]).

4.1 The severe double lane-change manoeuvre – test drive No. 6

The severe double lane-change manoeuvre according to ISO 3888-1 was test drive No. 6. The selected monitored quantities recorded in the course of test drive No. 6 with the real bus and calculated at simulations with the TriHyBus multibody model are given in Figures 5 to 7.

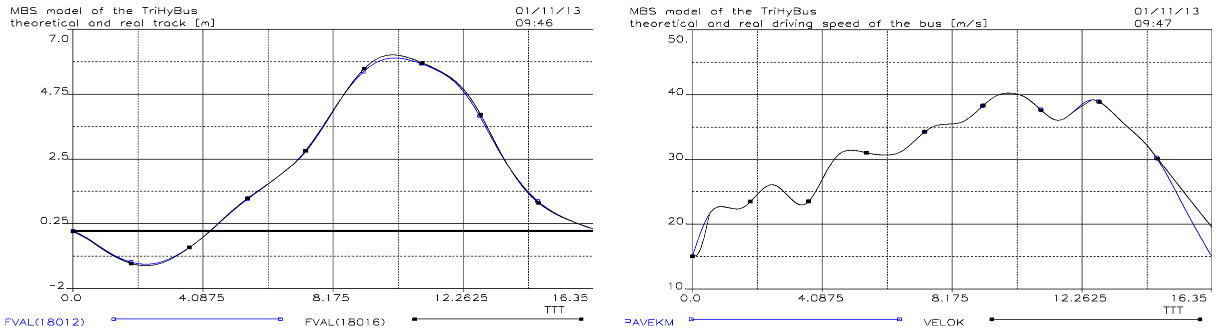

Figure 5: a) Time histories [s] of the bus trajectory [m] calculated on the basis of records at experimental measurements (FVAL(18012), in blue) and trajectory of the bus multibody model FVAL(18016), in black); b) time histories [s] of the bus speed [m/s] recorded at experimental measurements (PAVEKM, in blue) and bus multibody model speed (VELOK, in black).

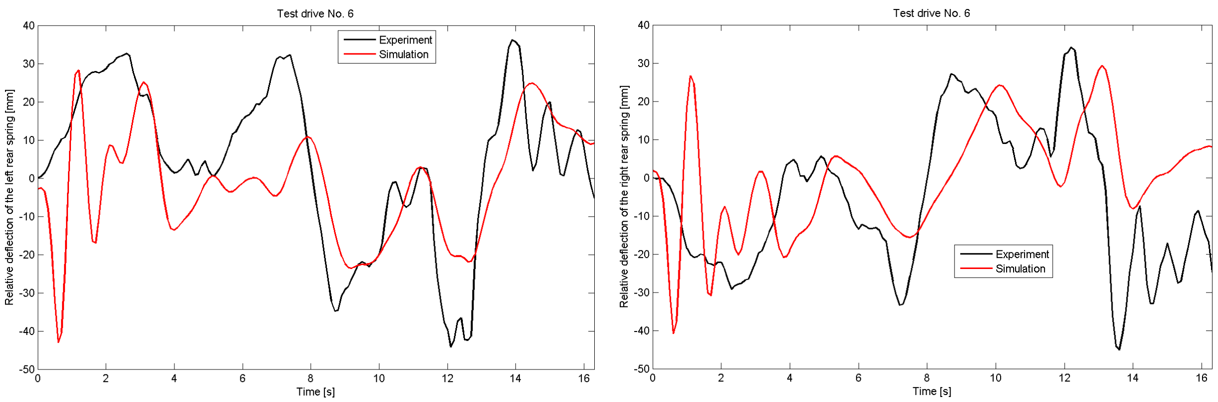

Figure 6: a) Time histories [s] of relative displacement [mm] measured on the left spring before the bus rear axle at experimental measurement and relative displacement [mm] of the left spring before the rear axle of the bus multibody model; b) time histories [s] of relative deflection [mm] measured on the right spring before the bus rear axle at experimental measurement and relative deflection [mm] of the right spring before the rear axle of the bus multibody model.

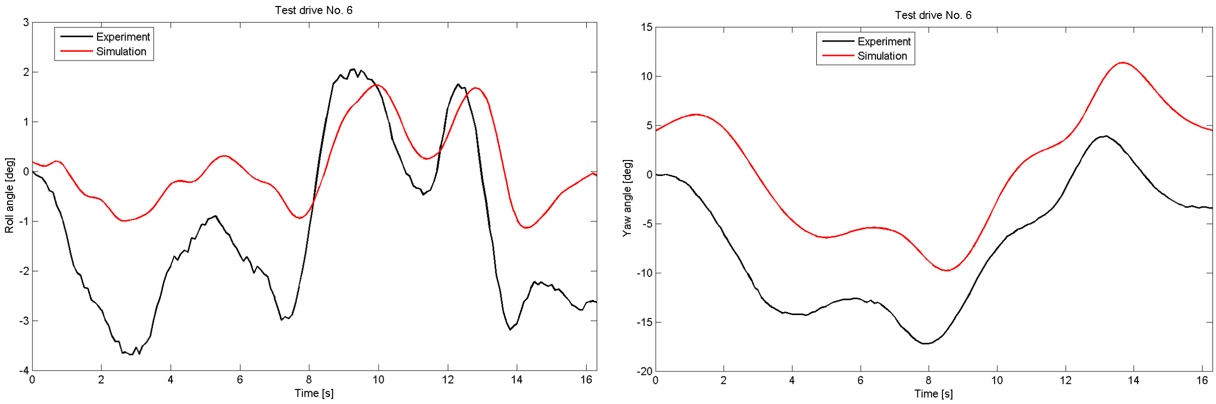

Figure 7: a) Time histories [s] of the vehicle roll angle [deg] (around the longitudinal axis) recorded at experimental measurement and the roll angle of the bus multibody model; b) time histories [s] of the vehicle yaw angle [deg] (around the vertical axis) recorded at experimental measurement and the yaw angle of the bus multibody model.

4.2 A “moose” test – test drive No. 10

A “moose” test was test drive No. 10. Selected monitored quantities recorded at test drive No. 10 with a real bus and calculated at simulating with the TriHyBus multibody model are shown in Figures 8 to 10.

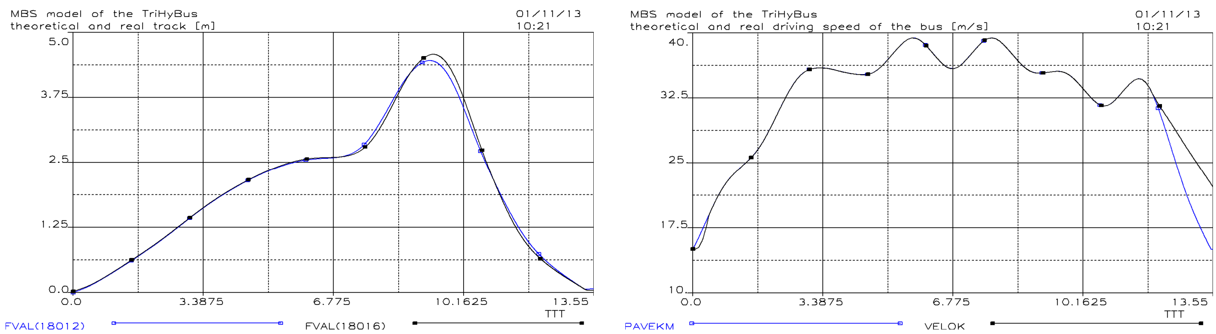

Figure 8: a) Time histories [s] of the bus trajectory [m] calculated on the basis of records at experimental measurements (FVAL(18012), in blue) and trajectory of the bus multibody model (FVAL(18016), in black); b) time histories [s] of the bus speed [m/s] recorded at experimental measurements (PAVEKM, in blue) and bus multibody model speed (VELOK, in black).

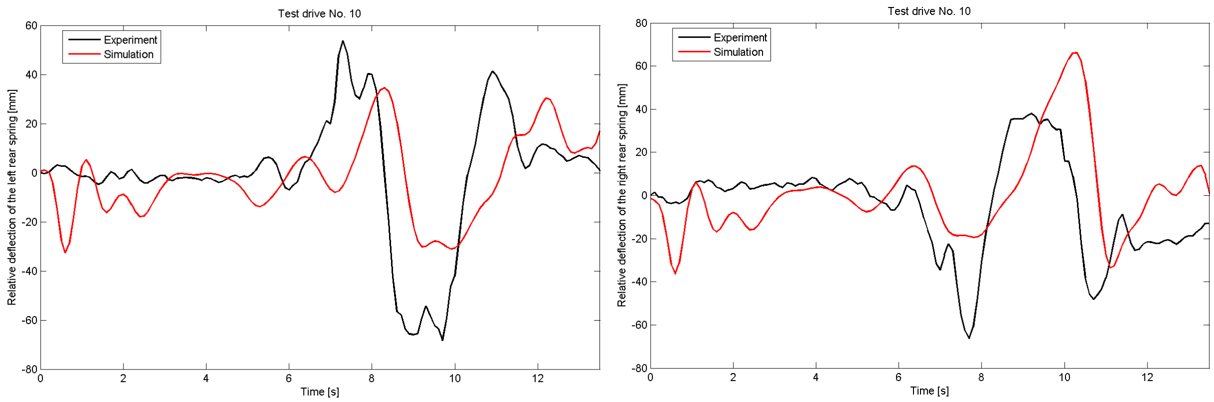

Figure 9: a) Time histories [s] of relative displacement [mm] measured on the left spring before the bus rear axle at experimental measurement and relative deflection [mm] of the left spring before the rear axle of the bus multibody model; b) time histories [s] of relative displacement [mm] measured on the right spring before the bus rear axle at experimental measurement and relative deflection [mm] of the right spring before the rear axle of the bus multibody model.

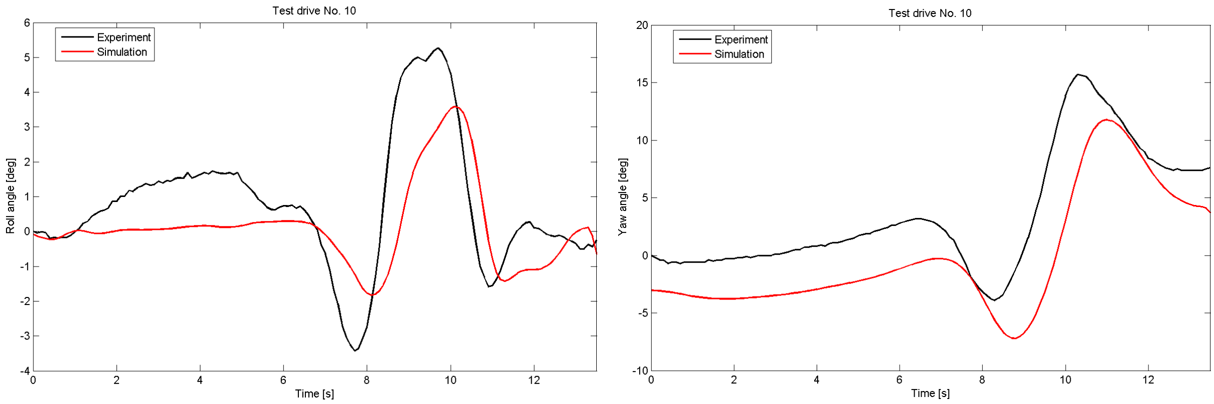

Figure 10: a) Time histories [s] of the vehicle roll angle [deg] (around the longitudinal axis) recorded at experimental measurement and the roll angle of the bus multibody model; b) time histories [s] of the vehicle yaw angle [deg] (around the vertical axis) recorded at experimental measurement and the yaw angle of the bus multibody model.

5 EVALUATION OF RESULTS

From the comparison of results of experimental measurements and simulations mentioned in Chapter 4 it is evident that certain coincidence of results exists but it is not perfect.

The characters of time histories of the monitored quantities recorded during the experimental tests with the real TriHyBus and calculated during the simulations with the multibody model are relatively identical, especially in the “second part” of the records. The “first part” of the records during the simulations has more significant character of transient vibration. As it has been stated the simulation of the test drive starts in the moment, in which the real TriHyBus reaches the speed of 15 km/h. The trajectory of the “mean wheel” motion is chosen in such a way that it should follow up the trajectory of the motion in the “monitored” section, i.e. the section in which the minimum bus speed is higher than 15 km/h, as continuously as possible. The character of the “first part” of records did not improve even at considering the longer “monitored” section, i.e. the section, in which the minimum bus speed is higher than 10 km/h (as it was tested). A certain possibility of improving the coincidence of the “first part” of records, which will be verified, is “tuning” the initial position of the bus multibody model in such a way that it should be an equilibrium position at the same time. The bus body roll angle and the bus body yaw angle, which were measured during the test drive in the moment of the real TriHyBus achieving the speed of 15 km/h, should be introduced as intitial conditions in addition. Other possibility of starting the simulation from the zero bus speed is not suitable due to the fact that in the course of the acceleration of the vehicle multibody model its speed is always lower than the required speed (which is given by the way of modelling, which cannot be satisfactorily replaced; this fact is evident from Figures 6, 7, 9 and 10) and especially at simulating the bus start the tire model “slipping” can occur. Obtained results of the simulations would be even more distorted than the existing ones.

The ignorance of the real air pressure in air springs of the bus suspension has the most significant impact on not completely perfect coincidence of results of experimental measurements and simulations. The significant impact of air pressure in air springs on the TriHyBus behaviour at test drives focused on the bus driving stability is evident from the recorded time histories of the springs relative deflections after finishing the manoeuvre (after the bus stopping) [4, 5]. The measured relative displacements between the rear axle and the chassis frame (at the left air spring and at the right air spring) comparing to the state before the driving manoeuvre start are different (see [4, 5]). The existing model of air springs in the bus multibody models considers the functional dependence of the force acting in the spring on the spring deformation, which was determined on the basis of the spring static loading. Knowledge of air pressure in springs would enable, in addition, to consider dependence of the force acting in the spring on the air pressure in the spring (see [5]).

6 CONCLUSIONS

Results of simulations of severe double lane-change manoeuvre according to ISO 3888-1 and a "moose" test (with the empty bus multibody model created in **alaska** simulation tool), which were performed with a real bus in Mělník (Czech Republic) in November 2012 [4, 5], are given in this paper.

From comparing the results of experimental measurements and simulations it is evident that a certain coincidence of results exists but it is not perfect. The ignorance of the actual air pressure in air springs of the bus suspension has the most significant impact on the coincidence of the results of experimental measurements and simulations, which is not perfect. In case of further possible test drives with the real TriHyBus it would be necessary, due to defining bus multibody models more precisely, to measure pressure in air springs. In the existing model of air springs in the bus multibody model the functional dependence of the force acting in the spring on the spring deformation, which was determined on the basis of the spring static loading, is considered. In the more precisely defined model dependence of the force acting in the spring on the air pressure in the spring would be considered in addition.

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