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INVERSE MULTIBODY SIMULATIONS FOR MOTORCYCLE TIRE FORCE ANALYSIS

TOBIÁŠ Martin[1*], STRAKA Tomáš[1], PORTEŠ Petr[1]

[1] *Institute of Automotive Engineering, Faculty of Mechanical Engineering, Brno University of Technology, Technická 2896/2, Brno, Czech Republic. e-mail: martin.tobias@vut.cz*

Abstract: This paper examines the use of inverse multibody system simulations, focusing on its application in the automotive industry, particularly in the context of motorcycle dynamics. The study emphasizes the importance of accurately measuring various parameters, including the calibration of sensors and the determination of motorcycle kinematical description and weight distribution to build an accurate vehicle model. The research highlights the significance of the presented method in evaluating tire characteristics through different manoeuvres, such as ride resistances, longitudinal and lateral behaviours, and their combined dynamics. The results presented, demonstrate the correlation between the calculated tire forces and the motorcycle's acceleration during these manoeuvres. However, the study acknowledges challenges, such as potential inaccuracies due to the rider's movements and the limitations associated with sensor error and noise. The paper suggests potential remedies discussed in earlier research, urging further investigation into improving measurement accuracy and reliability in inverse multibody system simulations for motorcycles.

KEYWORDS: Motorcycle, Measurement, Multibody, Simulation, Analysis

1 Introduction

1.1 Direct multibody simulations

One of the most common type of simulations in automotive industry is a multibody system simulation. This type of approach describes all the important moveable parts of given mechanical system by dynamic equations. While a plethora of commercial software solutions exists in this domain, this paper specifically adopts the utilization of SAMS (Symbolic Analysis of Mechanical Systems), a multibody system software developed by Porteš [1]. This methodology aligns with similar strategies outlined in publications written by Bartolozzi [2], Vasquez [3] or Cheli [4]. Moreover, multibody simulations are a industry standard in many engineering applications, not limited to automotive sector.

With these software tools, engineering teams can create and test working virtual prototypes of complete vehicles and vehicle subsystems. This can also be done by implementing co-simulations using different software tools as demonstrated by Magdolen [5]. In this way, the same tests that are normally performed in a test lab or on a test machine or track can be performed, but in a fraction of the time. In the case of vehicles, this is most often done to predict vehicle behaviour, to investigate 'what if' scenarios and to perform sensitivity analyses such as Magdolen [6] and HaoLiang [7].

For complex direct multibody vehicle simulations, in addition to the vehicle itself, it is necessary to model the boundary conditions of the test, in particular the road, steering, tires, define the test scenario and the required outputs. The properties of these models can then be changed and changes in the variables in the individual tests can be monitored. However, the reliability of the results obtained in this way depends on the quality of the models created, or

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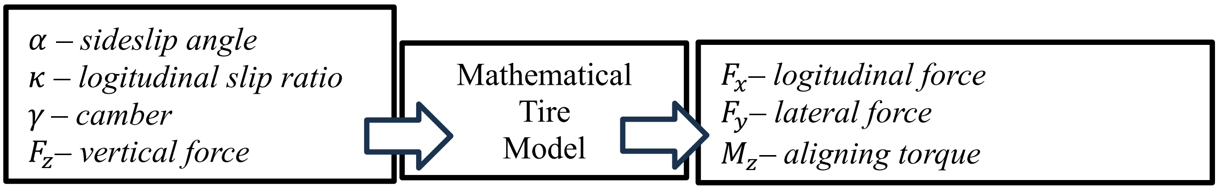
the degree to which they correspond to reality. Therefore, the best way to validate the simulation results is still to test the selected scenarios in reality.

1.2 Inverse multibody simulations

The main use case of SAMS is that it allows to perform inverse multibody simulations, which are designed to reconstruct real vehicle test rides, during which the necessary physical quantities are sensed on the vehicle. The measured signals are coupled with a SAMS inverse multibody model that computes the dynamic states of the vehicle. The basic principle of this coupling is the equality of measured and computed signals from real and virtual sensors. In order to identify the parameters of the tire model, it is necessary to have both input and output variables of the tire model. It is also necessary to determine the position of the tire contact point with the road. Typical input and output quantities of a basic tire model are shown in in the following diagram and symbolic equation (1).



$$\begin{bmatrix} \boldsymbol{F_x} \\ \boldsymbol{F_y} \\ \boldsymbol{M_z} \end{bmatrix} = f(\alpha, \kappa, \gamma, F_z) \tag{1}$$

By utilizing inverse multibody simulations, some of the inherent inaccuracies of direct simulations can be eliminated, because the output variables are calculated by SAMS, without the need for a road, driver or tire models. In here, lies the main advantage of this method, which is the ability to calculate certain physical quantities not measured during the test, including the forces between the tires and the road. The reliability of these results depends mainly on the quality of the recorded data, the match between the multibody vehicle model and the real vehicle and the accuracy of the initial static calibration of the vehicle measurement system. Usually, it is demanding to create a valid multibody description of a vehicle, yet versatility of SAMS allows comprehensive description of any vehicle in a great detail. Examples of such a vehicle is shown in Figure 1.

Fig. 1 - Experimental vehicles – VW Multivan and KTM RC 390

SAMS can be used for any road vehicle, yet for purpose of this paper a KTM RC390 motorcycle was chosen. Motorcycle dynamics compared to two-tracked vehicles brings more challenges e.g., increased tilting of the vehicle, more vibrations, significant load transfer and other difficulties. Despite those problems, numerous valid results were achieved of which some are presented in this paper.

This methodology is a great alternative for evaluation of tire forces and whole tire models, which are done in laboratory conditions. Most of the tire characteristics tests are done on Flat-Trac [8] or special measuring trailer [9]. However, the adoption of a modified measurement vehicle coupled with SAMS introduces a unique opportunity to evaluate tire characteristics using real-world road data. This approach strives to closely replicate the authentic conditions experienced by tires during their operation.

Fig. 2 - Flat-Trac and a measuring trailer [6],[7]

2 Experimental investigation

2.1 Experimental motorcycle setup

For the purpose of the research, a KTM RC390 motorcycle was used. Its parameters (kinematic points, centre of gravity position, moments of inertia, spring stiffness, shock absorber characteristics, engine power output characteristic, etc.) were measured in the laboratory. Based on the measured parameters, a multibody model of the experimental motorcycle was created in SAMS and linked to the measured data using Telematrix software [10] developed by Zháňal. In addition, the dynamic model of the motorcycle contains elements with known (measured; e.g., forces acting from the spring damping units) and unknown force effects, the magnitude of which is calculated from vehicle motion (tire forces, driving or braking moments, chain forces, aerodynamic lift forces.

Table 1. Overview of used sensors

Measured quantities	***Sensor***
Speed and acceleration of the vehicle	OXTS RT 3002
GPS coordinates and heading	OXTS RT 3002
RPM of wheels, engine and position of the throttle valve	CAN Bus
Positions of front and rear fork	Linear potentiometer
Steering angle	Linear potentiometer
Damper forces	3x strain bridge
Motorcycles position relative to the ground	7x Texense RHS
Brake pressure	2x Baumer PBM4
Acceleration of the sprung and unsprung masses	4x Kistler 8315A

As meantioned earlier, the experimental vehicle needs to be equipped with a diverse array of sensors. Various optical and electro-mechanical sensors are used for measuring the required physical quantities of the motorcycle during a test ride. The motorcycle is equipped with a highly precise GPS and inertial system, responsible for tracking the motorcycle chassis global positions and recording its acceleration profiles. A comprehensive inventory of all employed sensors is presented in Table 1, and their strategic placements are visually depicted in Figure 3.

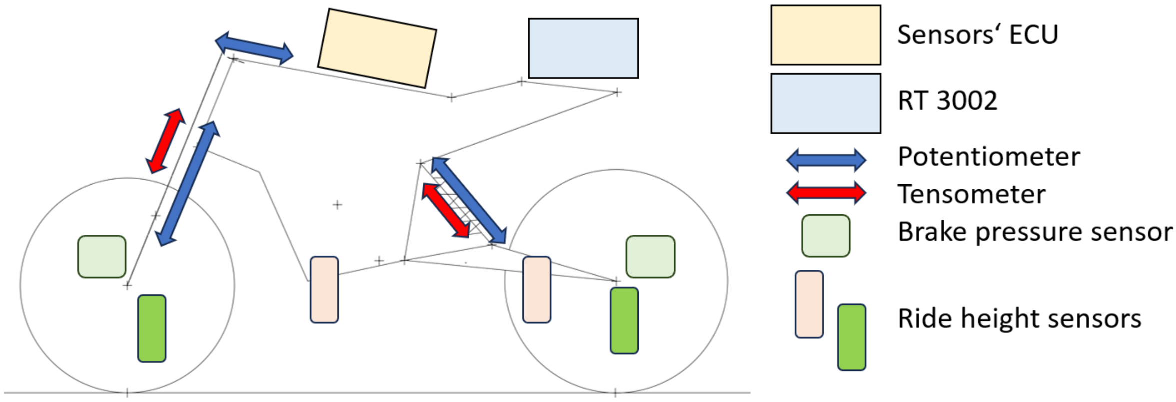


Fig. 3 – Sensor placement on the experimental motorcycle

2.2 Experimental test rides

The initial recorded condition involves the motorcycle in a stationary state, where it is positioned perpendicularly to the ground, accounting for its complete curb weight. This encompasses the presence of the rider atop the motorcycle, along with all operating fluids and additional components. The primary objective of this measurement phase is to meticulously calibrate the height and potentiometric sensors, ensuring their accurate functionality. Subsequently, this calibration procedure is iterated with the motorcycle positioned atop scales beneath both wheels. This facilitates the precise determination of the motorcycle's overall weight and offers insights into its weight distribution across its wheels.

For description of tire characteristics, it is necessary to measure pre-planned manoeuvres. Although measuring on public roads is possible and, in some cases, even demanded, for this application a place with as even road surface as possible was chosen to eliminate measured noise. The Continental’s testing track and facilities in Otrokovice were chosen for its free space to fit all the manoeuvres and elimination of all the possible dangerous traffic situations on public roads – to ensure safety.

First actual road test was a measurement of ride resistances. It is necessary to determine rolling resistance of wheels and air resistance of the motorcycle. That was done by accelerating to a specific speed and then engaging the clutch and letting the motorcycle to slow down by its ride resistances. Since this measurement took very long trajectory, it was necessary to divide this measurement by specific speed intervals and then connecting them while evaluating the data in the postproduction. Slope resistance was eliminated by an even road. After this measurement, the motorcycle was prepared and tuned to be used by SAMS to evaluate the forces interacting in between all the described motorcycle’s components.

The next described experiments can be divided into two categories: longitudinal and lateral. Longitudinal behaviour of tires ensures motorcycle’s ability to accelerate and decelerate. Measuring this characteristic is relatively simple. The goal of this manoeuvre is to ride in a straight line and accelerate the motorcycle. Various engine loads were be included. The same approach is taken while braking, with the addition of separation of front wheel and rear wheel braking.

Lateral behaviour of tires ensures motorcycle’s ability to turn and stability while cornering. Due to high noise, it is necessary to measure as stable states as possible. Due to this fact, it was decided to measure motorcycle's turning in a circle with a constant radius, while gradually increasing motorcycle's speed and maintaining it for a specific amount of time in each step.

The last manoeuvre was an attempt to combine both longitudinal and lateral dynamics. The goal of the manoeuvre is to maintain the lean angle, while increasing speed of the motorcycle and the turn radius.

After the completion of all manoeuvres, each measurement undergoes a series of preparatory steps, including signal filtration, time synchronization, and editing. Then SAMS comes into play for the comprehensive evaluation of all investigated variables. These encompass quantities such as damper and spring forces, as well as tire forces, tire slips, and slip angles, among others. For easier display of evaluated data and communication with SAMS, TeleMatrix was used.

3 Results and discussion

First step for correct evaluation is an accurate calibration of all the sensors. This can be also checked in TeleMatrix in vehicle visualization. The results are shown in Figure 4. It is visible that all the motorcycle parts are placed correctly, fitting in each other and the motorcycle itself is placed accordingly to the ground.

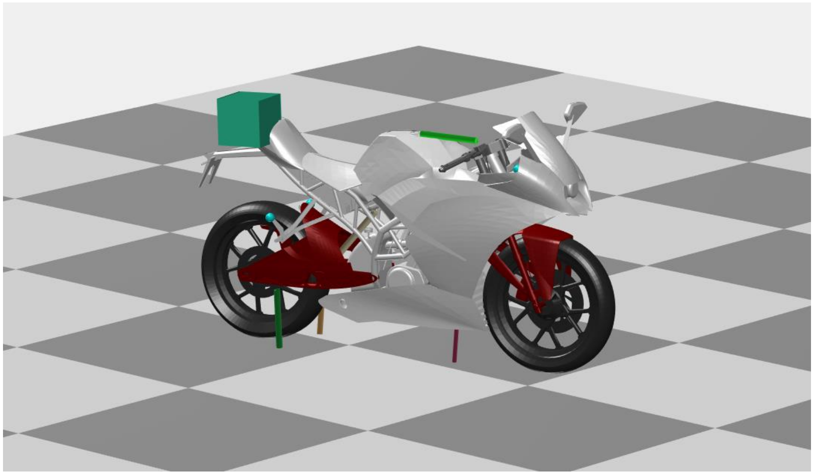


Fig. 4 – Visualization of the motorcycle in Telematrix

When it comes to the actual manoeuvres, not all of them were successfully measured without encountering challenges. Specifically, the circle tests and parabolic manoeuvres faced issues arising from inadequate GPS synchronization. This issue is likely attributed to extended intervals of low speed, which adversely affect the accurate approximation of the motorcycle's heading. This phenomenon can be seen in Figure 5. It's visible that the measurement was correct for some amount of time, but once the motorcycle slowed down, its measured coordinates started to drift more and more. Unfortunately, the quality of the data measured from those manoeuvres is not sufficient to serve as SAMS' inputs.

A sample of acceleration tests' results can be seen in *Figure 6*. All the graphs show quantities synchronized in time. In the upper graph, the throttle position is shown. That serves as a simple description of this manoeuvre – the rider used full throttle, starting from a standstill, shifting three gears up total. In the lower graph longitudinal acceleration is shown. According to theory, the acceleration should be corresponding with the evaluated force on the wheels, which are shown in the middle graph. It is visible that the rear wheel force correlate with the acceleration. During shifting gears, the rear wheel force is negative. That is caused by the rear wheel's RPMs synchronizing with engine's RPMs after the shift. The front wheel serves in this case as a flywheel, slightly braking during motorcycle acceleration and slightly powering up the motorcycle during its deceleration. Compared to the motorcycle's mass and it's acceleration, both the front wheel force and rear wheel force calculated values are in their expected ranges.

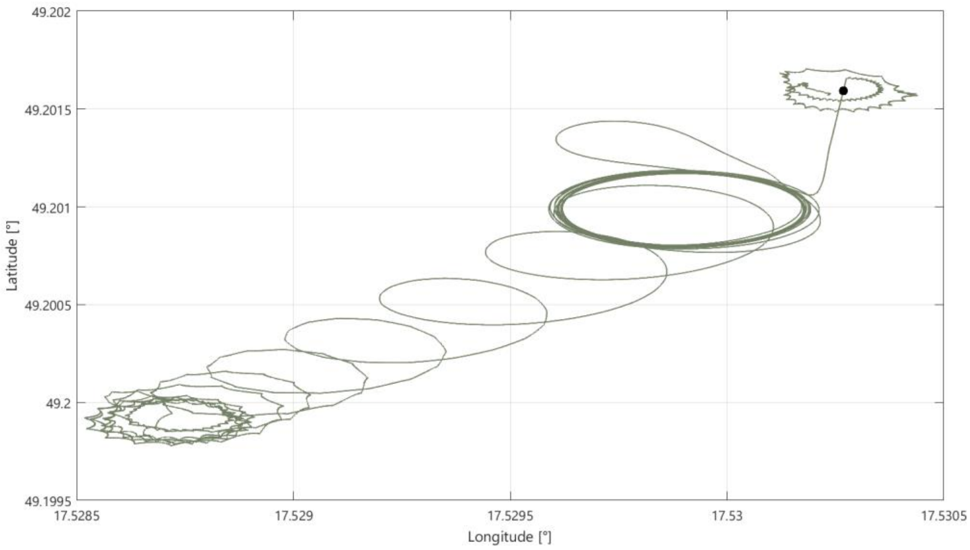


Fig. 5 - Incorrectly measured GPS coordinates

In *Figure 7*, there are braking tests results. Again, for better imagination of the manoeuvre, brake pressure is shown in the upper graph and longitudinal acceleration in the lower graph. The rider braked with the rear brake until the rear wheel had been blocked, which can be seen in the upper graph slightly before 90 second mark. The correspondence between the rear wheel force and longitudinal deceleration can be seen. Also note that the increasing the brake pressure does not necessarily bring an increase in the wheel's brake force. That is caused by an excessive wheel slip through load transfer and, in the end, locking of the wheel. Normally, this would be prevented by ABS, but for sake of this experiment this system was turned off.

Lastly, it is necessary to mention shortcomings of this method. The incorrect GPS calibration was mentioned. GPS base station needs to be also used, which limits the area able to perform the experiments. All the sensors and equipment is vulnerable to water, so the tests need to be performed in dry conditions. During the manoeuvres, big load transfers happen. Motorcycle load transfers are calculabled by SAMS, but there was no way how to monitor shifting mass centre of the rider. During all the tests, the goal of the rider was to move as little as possible, yet this approach brings some error in the calculations. Possible solution of this problem was described in publications by Cheli [11] or Bocciolone [12].

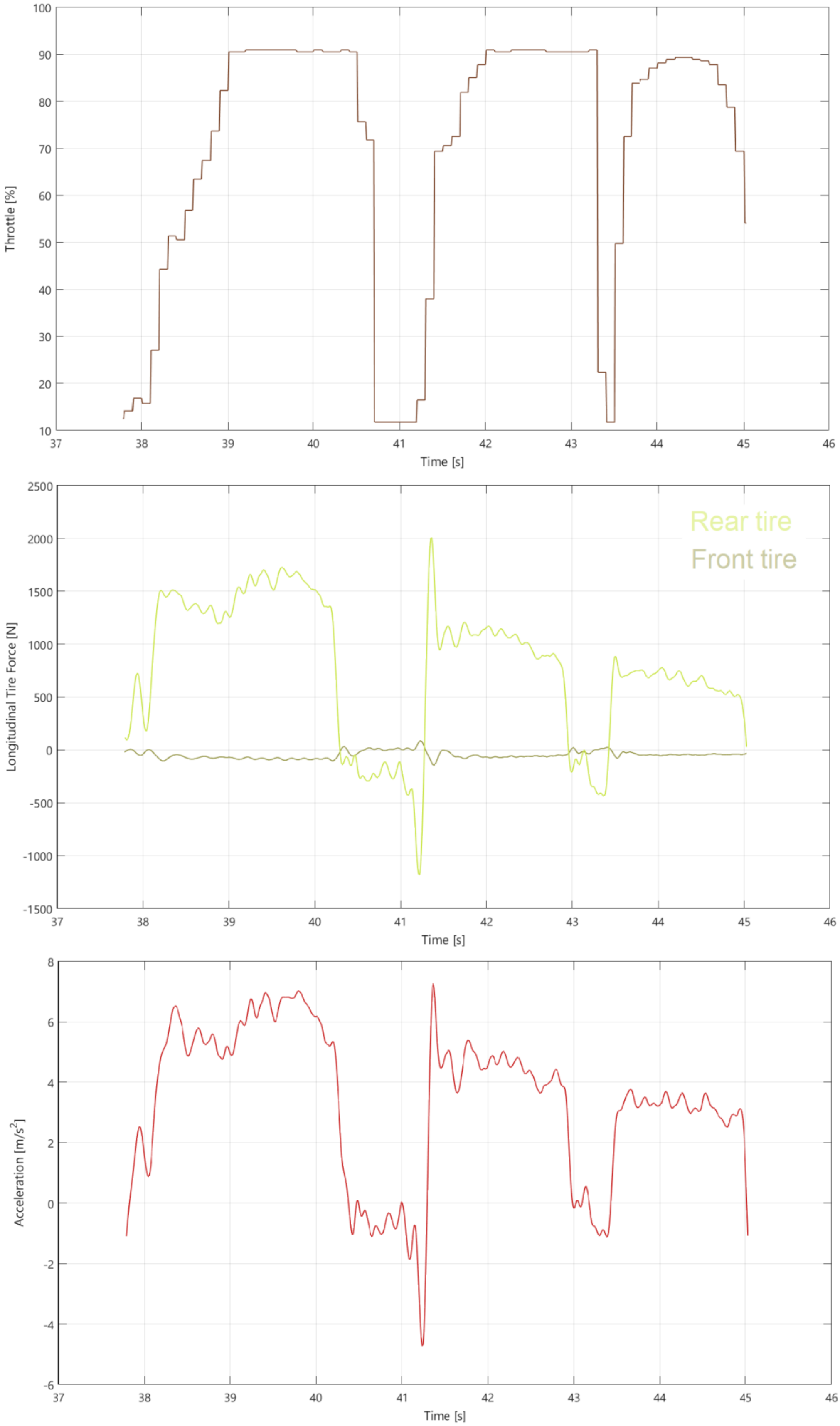


Fig. 6 – Acceleration (upper – throttle, middle – tire forces, lower – acceleration)

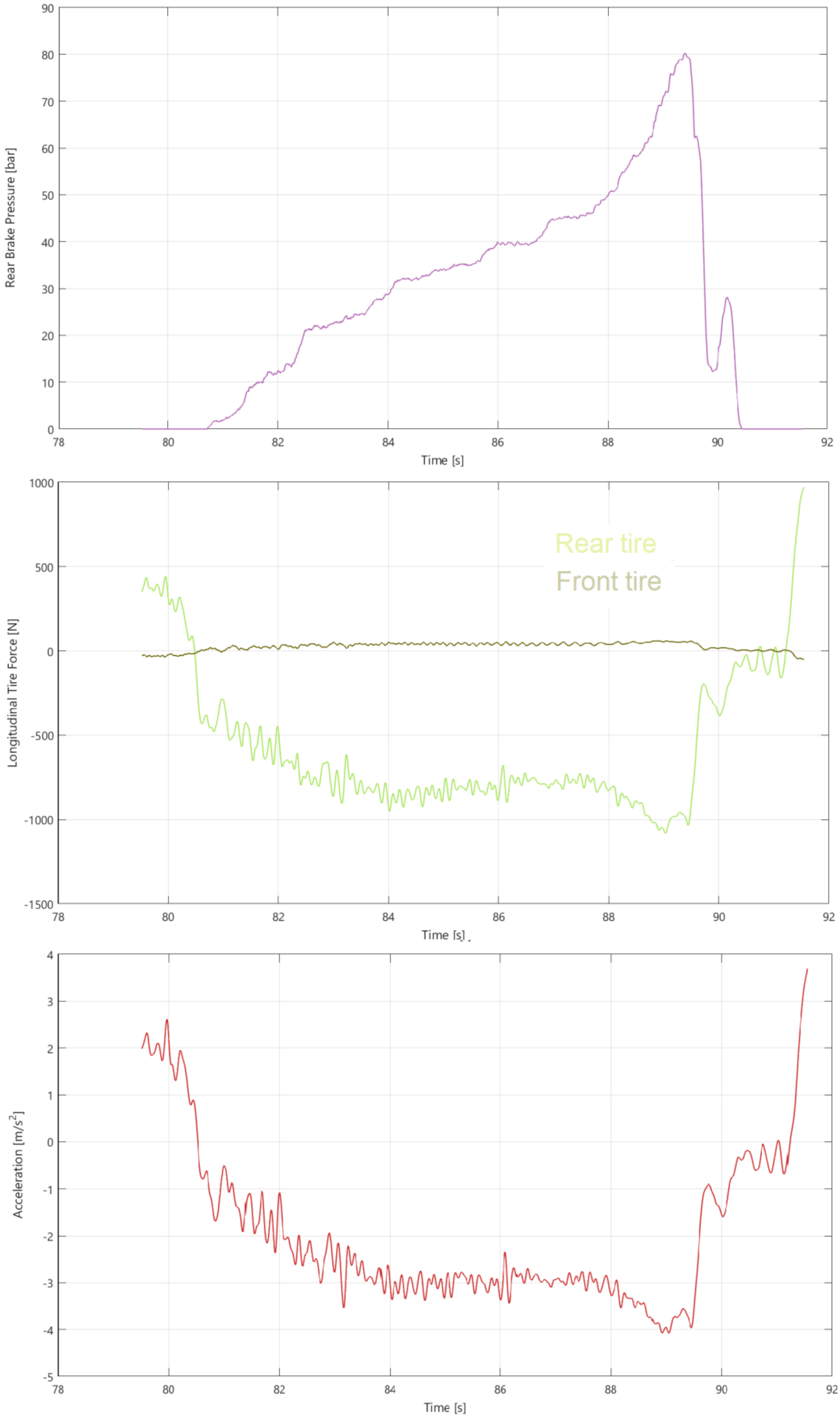


Fig. 7 – Deceleration (upper – rear brake pressuretle, middle – tire forces, lower – acceleration)

CONCLUSION

This study has effectively presented the foundational concept and advantages associated with employing a reverse multibody model within motorcycle dynamics analysis. Despite the inherent challenges and limitations, this model has demonstrated its capacity to assess longitudinal forces acting between the tire and the road surface – a complex parameter often eluding conventional assessment methods. By further improvements of the used GPS inertial measurement system, more complex manoeuvres are expected to be evaluated. Furthermore, a continued enhancement of the motorcycle's SAMS model holds the promise of uncovering critical dependencies such as tire slip/force characteristics and tire stiffnesses. This brings an opportunity for accelerated tire testing and tire models development, thus presenting significant implications for the field of vehicle dynamics.

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REFERENCES

[1] Porteš, P. “Utilisation of mathematical vehicle models in analysis of measured data“, habilitation thesis, Brno University of Technology, **2015**.

[2] Bartolozzi, M., Savino, G., Pierini, M. “Novel high-fidelity tyre model for motorcycles to be characterised by quasi-static manoeuvres - rationale and numerical validation”, Vehicle system dynamics 60 (12), pp. 4290 – 4316, **2022**. DOI: 10.1080/00423114.2021.2013506

[3] Vasquez, F., Lot, R., Rustighi, E., Pegoraro, R. “Tyre forces estimation for off-road motorcycles”, Mechanical systems and signal processing 150 (4), p. 107228, **2021**. DOI: 10.1016/j.ymssp.2020.107228

[4] Cheli, F., Mazzoleni, P., Pezzola, M., Ruspini, E., Zappa, E. “Vision-based measuring system for rider's pose estimation during motorcycle riding”, Mechanical systems and signal processing 38 (2), pp. 399 – 410, **2013**. DOI: 10.1016/j.ymssp.2013.01.009

[5] Magdolen, Ľ., Danko, J., Milesich, T., Kevický, I., Hanko, L., Skyrčák, R. "Conditions for Loss of Stability of an Autonomous Vehicle During a Cornering Manoeuvre" Strojnícky časopis – Journal of Mechanical Engineering 72 (3), pp.129 – 140, **2022**. DOI: 10.2478/scjme-2022-0047

[6] Magdolen, Ľ., Danko, J., Milesich, T., Kevický, I., Hanko, L., Galinský, M., Bucha, J., Skyrčák, R. "Virtual Simulation of Overtaking Maneuver of Autonomous Vehicle" Strojnícky časopis – Journal of Mechanical Engineering 71 (2), pp.179 – 188, **2021**. Doi: 10.2478/scjme-2021-0028

[7] HaoLiang, G., XiHui, M., XiaoYong, Y., Kai, L. “Research on the influence of virtual modeling and testing–based rubber track system on vibration performance of engineering vehicles”, Engineering review 38 (3), pp. 288 – 295, **2018**. DOI:10.30765/er.38.3.5

[8] Gim, G. H., Ji, A., Lin M., “Analysis on MTS Flat-Trac CT & SS”, emonamics, Cheng Shing Tire, South Korea, **2023**.

[9] Siemens Digital Industries Software ”Tire simulation and testing”, [online] Available at: https://plm.sw.siemens.com/en-US/simcenter/simulation-test/tire-simulation-testing/?pk_vid=5ef38bb7b701334f1e91e1289b25d91d1715943524987f51#76rDeh3Ezt12NEw75KF5UN [Accessed: 19-11-2023].

[10] Zháňal, L., Porteš, P. "Universal Tool For Data Analysis", Perner's contacts 11 (4), pp. 136 – 143, **2016**. [online] Available at: https://pernerscontacts.upce.cz/index.php/perner/article/view/581/420 [Accessed: 09-11-2023]

[11] Cheli, F., Pezzola, M., Taroni, N., Mazzoleni, P., Zappa, E. "Driver's movements influence on the lateral dynamic of a sport motorbike", In 2011 19th Mediterranean Conference on Control & Automation (MED), Corfu, pp. 916 – 921, **2011**. DOI: 10.1109/MED.2011.5983207

[12] Bocciolone, M., Cheli, F., Leo, E., Pezzola, M. "Experimental Identification of a Motorcycle Rider 3D Movements on a Running Vehicle", In Volume 2: Automotive Systems, Bioengineering and Biomedical Technology, Fluids Engineering, Maintenance Engineering and Non-Destructive Evaluation, and Nanotechnology, Torino, pp. 101 – 104, **2006**. DOI: 10.1115/ESDA2006-95310