Tire Concept Investigation for Wheeled Mobile Driving Simulators

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Abstract – Wheeled Mobile Driving Simulators (WMDS) promise a high potential for urban traffic simulation. The tires generate the accelerations of WMDS and therefore are a key component of this simulator type. Hence, the choice of a proper tire concept is of high importance. Solid tires with compact dimensions and a high vertical stiffness are a possible alternative approach to pneumatic tires. To assess the application potential of solid tires their characteristics are identified. The results show that high slip values and slip angles are necessary to reach the maximum friction coefficient of about 0.8 while their correlation is highly nonlinear. With the identified tire properties the impact of the tires on energy consumption and motion control performance of WMDS is investigated. The solid tires show an increased energy consumption of about 4% compared to pneumatic tires in representative urban driving cycle simulations. Solid tires with their nonlinear characteristics lead to five times higher lateral acceleration errors in relation to pneumatic tires at accelerations of 5 m/s² during a horizontal eight maneuver. The vertical properties of both tires were identified to be not sufficient for the application of a WMDS solely sprung by tires on uneven grounds of common quality.

Keywords: Wheeled Mobile Driving Simulator, Solid Tires, Pneumatic Tires, Analysis, Simulation.

Introduction

Wheeled Mobile Driving Simulators

Driving simulators are an important instrument in the research of the still increasing field of driver assistance systems. In this regard a high potential in the simulation of complex urban scenarios arises which leads to huge demands on the dynamic motion representation of driving simulators. To meet these demands the motion simulation system of today’s state-of-the-art driving simulators consists of a hexapod for the representation of low frequent accelerations mounted on a sledge system which enables high frequent motions. Nevertheless a long travel distance of the sledge system is necessary to meet the requirements of urban scenarios [Bet12]. Due to the system immanent coupling of range of motion and moving mass this results in an increased power demand and therefore leads to an enormous technical and financial effort [Zee10].

Hence, to widen the application potential of driving simulators on urban traffic it is necessary to eliminate the coupling between motion range and moving mass. An approach to solve this dilemma is a tirebound wheeled mobile driving simulator (WMDS) with a motion base actuated by steerable driven wheels instead of a sledge system.

Previous research at the Institute of Automotive Engineering (FZD) dealt with the practical feasibility of the concept referring to power, energy and friction demand [Bet12a, Bet12b, Bet14b] as well as the control [Bet13] and safety architecture [Bet14a]. Besides simulative studies the hardware-prototype MORPHEUS shown in Figure 1 was built to validate the simulation results [Wag14]. It consists of a motion platform which is actuated by three wheel units each with one electric steering and one drive motor. A Hexapod is mounted on top of the platform for the acceleration simulation through Tilt Coordination (TC). The previous results are summarized in the dissertation of Betz [Bet15].

Figure 1: WMDS prototype MORPHEUS
Tire Concept

The tire as a key component for this type of simulators requires extensive investigations for a sound development of WMDS. Different operation boundary conditions of driving simulators in comparison to typical passenger cars utilizing pneumatic tires open the possibility to use alternative tire concepts. Lower velocities and driving surfaces of high quality allow the use of solid tires with high vertical stiffness. This leads to lower acceleration induced pitch and roll movements of the driving simulator that potentially would deteriorate driver immersion. Additionally, solid tires have a high load capacity in relation to their size, which leads to a compact package and a low center of gravity (CG) of the wheel unit. The low CG on the other hand results in a smaller overall system because of the reduced necessary lever arms for rollover stability.

The aim of this paper is to characterize the solid tires concerning the usability for WMDS and compare their performance with pneumatic tires. The tire characteristics measurement which is necessary for the assessment is presented in the first part of the paper. The second section aims at answering the question about the impact of the specific tire characteristics of solid tires on the development of WMDS in comparison to pneumatic tires. Therefore the advantages and disadvantages of the tire will be quantified. The last part of the paper opens a new research field concerning the vertical dynamics of WMDS by comparing the performance of solid and pneumatic tires on uneven surfaces.

Tire Measurements

The following section describes the tire characteristics identification of the GUMASOL press on band tires [Gum16] installed in the MORPHEUS prototype.

Longitudinal Tire Characteristics

The longitudinal tire measurements determine the friction coefficient vs. longitudinal slip curve.

Methodology

The longitudinal tire measurements are carried out using the MORPHEUS prototype. One of the drive motors is actuated by setting a target wheel rotation speed \( \omega_{\text{rot,w,\text{set}}} \) which is calculated from the given slip \( \lambda_{\text{set}} \), the effective roll radius \( r_e \), and the velocity \( v_{\text{sim}} \):

\[
\omega_{\text{rot,w,\text{set}}} = \frac{v_{\text{sim}}}{r_e} (1 + \lambda_{\text{set}})
\]

The required velocity is determined with GPS, an integrated acceleration sensor, and an optical velocity sensor (Correvit S400 [Cor03]), whose signals are merged by a GeneSys ADMA G [Gen15]. The effective roll radius is calculated from the rolling circumference that was measured beforehand. The set rotational speed of the drive motor leads to slip at the tire contact patch. The tire force \( F_{T,x} \) resulting from that slip is determined by measuring the longitudinal acceleration \( a_x \) of the prototype with a GeneSys ADMA G. Not the whole tire force is transposed into acceleration due to the driving resistance force \( F_R \):

\[
F_{T,x} = m_{\text{sim}} a_x + F_R
\]

The driving resistance force is identified by deactivating the drive motors at the end of a test run and measuring the resulting deceleration while coasting. By multiplying the deceleration with the simulator mass \( m_{\text{sim}} \) the driving resistance force is determined. Afterwards the longitudinal tire force is calculated with formula (2).

The next step is the determination of the friction coefficient by dividing \( F_{T,x} \) by the wheel load \( F_{T,z} \). The wheel load calculation considers the static load as well as dynamic wheel load transfer resulting from the measured longitudinal acceleration. The measurements were carried out with two different static wheel loads at 3500 N and 4500 N to identify the wheel load sensitivity of the friction coefficient.

Results

The results of the longitudinal friction coefficient measurements are shown in Figure 2. It is recognizable that the maximum friction coefficient of approximately 0.85 is reached at high slip values between 40 % and 50 %.

![Figure 2: Friction coefficient vs. longitudinal slip](image)

The friction coefficient is slightly decreasing with higher wheel loads. Although the qualitative behaviour of pneumatic tires with a declining characteristics of friction coefficient over slip is recognizable the nonlinearity up to the maximum friction coefficient is more distinct. Furthermore
there is almost no decrease of friction coefficient at higher slip values.

**Lateral Tire Characteristics**

This section describes the determination of the lateral force and friction coefficient versus slip angle behaviour.

**Methodology**

The experimental setup for the measurement of lateral forces shown in Figure 3 is based on the MORPHEUS prototype with an adapted axle construction at one wheel. The desired slip angle at the tires is generated by setting a target angle at one of the steering motors. To avoid yaw moments an opposed steering angle is set at the opposite steering motor to compensate the lateral tire forces.

The simulator is driven by an external towing vehicle because the transmittable longitudinal force of the rear wheel is too low to overcome the resistance due to slip angles at the front wheels.

Though the lateral force is compensated a build-up of yaw angles of the prototype cannot be excluded especially at high slip angles where sliding occurs. In this case a deviation of steering angle and slip angle arises. For this reason, the slip angle is measured directly by an optical velocity sensor Correvit S400, which is steered together with the whole measurement wheel.

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**Results**

The determined friction coefficients are shown in Figure 5. The maximum lateral friction coefficient of about 0.9 is close to the longitudinal and therefore approves the measurements. Similar to the longitudinal force characteristics the maximum friction coefficient is reached at – compared to pneumatic tires - high slip angles of 30°.

Additionally the results show a high wheel load dependence of the lateral friction coefficient. A wheel load difference of 2800 N, which could occur by acceleration induced dynamic wheel load transfer, reduces the average friction coefficient from 0.85 to 0.7 (17.6 % reduction).

Below the friction coefficient the absolute value of the lateral force is of importance for the cornering behaviour. The results for this characteristic are shown in Figure 6.

The cornering stiffness for different wheel loads is shown in Table 1 for solid tires (ST). For a quantitative comparison the values of a reference pneumatic tire (PT) taken from [Pac12] are denoted. It is observable that the cornering stiffness
of solid tires is low compared to pneumatic tires and is almost not influenced by wheel load changes.

### Table 1. Cornering stiffness of pneumatic and solid tires

<table>
<thead>
<tr>
<th></th>
<th>F_{T_x} = 2 kN</th>
<th>F_{T_x} = 4 kN</th>
<th>F_{T_x} = 6 kN</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_{e,ST}$ in kN/rad</td>
<td>9.4</td>
<td>9.4</td>
<td>9.4</td>
</tr>
<tr>
<td>$c_{e,PT}$ in kN/rad</td>
<td>32.1</td>
<td>52.5</td>
<td>60.3</td>
</tr>
</tbody>
</table>

#### Impact on WMDS Design

The identified tire characteristics show noticeable nonlinearities and high necessary slip values for maximum friction coefficients. These influences have to be considered in the design of WMDS.

### Research Questions

Based on the tire measurement results the following research questions about the impact of tire characteristics on WMDS design can be formulated:

- How high is the increase of energy consumption induced by high longitudinal and lateral slip values of solid tires in representative application scenarios?
- Which acceleration deviations arise due to the low cornering stiffness and the nonlinearities of solid tires?

In the following an analysis of the presented questions is conducted. The results of solid and pneumatic tires are compared to assess the impact of solid tires.

### Research Tools

#### WMDS Model

The assessment of the tires’ impact on the simulator design is done via computer simulation. Therefore, the virtual prototype of the WMDS, which is modelled in IPG Carmaker and Simulink is applied. The basic structure of the model is shown in Figure 7.

The input into the model is an acceleration profile of a simulated vehicle. The available profiles vary from synthetic maneuvers such as 90° corners and horizontal eights with different maximum accelerations to representative urban driving cycles [Bet12].

These horizontal and rotational accelerations $\ddot{a}_V$ and $\ddot{\alpha}_V$ of the simulated vehicle are afterwards transformed into desired accelerations $\ddot{a}_{DS,ref}$ of the motion platform and necessary TC angles $\delta_{TC}$ of the hexapod with an ideal Motion Cueing Algorithm (MCA). It consists of a classical washout algorithm supplemented by a feedback from the TC [Bet15].

In the next step the desired motion platform accelerations are transformed into wheel steering angles $\delta_i$ and torques $M_i$ at the wheel hubs at each of the three wheels by the Motion Control (MC). These values are the input for the motion platform dynamics calculation in IPG Carmaker.

#### Tire Model

Carmaker offers a Simulink Interface, which is suitable to implement self-designed tire models. The horizontal tire behavior is modelled based on Pacejka’s fully non-linear single contact point transient tire model combined with the Magic Formula 5.2 [Pac12].

The tire model parameterization for the solid tire is done by fitting the model curves to the measured tire characteristics shown in Figure 2, Figure 5 and Figure 6. The horizontal tire model was validated statically and dynamically by using the maneuvers constant cornering, constant cornering with driven wheel and steering angle step.

Yet no pneumatic tire for the hardware prototype is available so that generic parameters of a passenger car tire with equal nominal wheel loads as the hardware prototype will be taken as reference. Therefore, a generic parameter set of a 205/60R15 91V tire with a nominal wheel load of 4000 N is used, which is given in [Pac12].

#### Impact on Energy Consumption

For the assessment of the tires’ impact on the overall energy consumption a realistic scenario for a WMDS application is necessary to have a representative occurrence of slip angles and longitudinal slip. Therefore, different urban driving scenario acceleration inputs are simulated with active MCA, TC, and washout for solid tires (ST) and pneumatic tires (PT). Recuperation is neglected so that the braking energy is fully dissipated. The results of the overall energy consumption of the drive motors are summarized in Table 2.

To make sure that the energy deviation between the tires does not result from acceleration errors induced by different tire characteristics the effective power acting on the CG is compared with a cross
correlation, which shows a high correspondence. As expected the results show an about 4% higher energy consumption if solid tires are used.

<table>
<thead>
<tr>
<th>Urban Scenario</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy ST in Wh</td>
<td>3123</td>
<td>2109</td>
<td>2011</td>
</tr>
<tr>
<td>Energy PT in Wh</td>
<td>3015</td>
<td>2017</td>
<td>1928</td>
</tr>
<tr>
<td>Difference in Wh</td>
<td>108</td>
<td>92</td>
<td>83</td>
</tr>
<tr>
<td></td>
<td>(3.6%)</td>
<td>(4.6%)</td>
<td>(4.3%)</td>
</tr>
</tbody>
</table>

### Impact on Motion Control

#### Introduction to Motion Control

The Motion Control (MC) concept which is presented was published in [Bet12, Bet13, Bet15]. It uses a kinetic model, which calculates the necessary forces in longitudinal and lateral direction at the three wheels from the desired accelerations resulting from the MCA. With the determined force demand at the tires the required wheel hub torque is calculated directly from the target longitudinal force in tire coordinates and the effective roll radius of the tire.

To determine the necessary steering angle of the wheels a kinematic model is used. Therefore, the velocity vectors resulting from the desired translational and rotational accelerations of the motion platform are calculated for each wheel. The angle between the resulting velocity vector and the x-axis of the driving simulator coordinate system is the necessary static steering angle if slip angles are neglected.

An enhanced algorithm of the MC also takes slip angles into consideration. It is based on the target lateral force in tire coordinates resulting from the force demand calculation. The geometric relations for this calculation are shown in Figure 8.

\[ \Delta = |\vec{F}_{w,i}| \cdot \sin(\delta_{w,kin,i} - \alpha_i) - c_{a,i} \alpha_i \] (3)

Afterwards the estimated slip angle is added to the static steering angle to determine the required overall steering angle for each wheel.

Earlier research has already shown that the characteristics of pneumatic tires have an influence on the control of WMDS and that the dynamic control with slip angle correction improves the performance of the MC [Bet13]. The following section analyses if solid tires lead to a worse behavior due to the reduced cornering stiffness and the higher nonlinearity.

#### Simulation and Results

The performance of the MC is mainly influenced by the described geometric relations and therefore by the lateral characteristics of the tire. To address the correlation between these characteristics the synthetic maneuver “horizontal eight” is applied as input signal. To assess the MC performance isolated from the MCA, the MCA is inactive so that the motion platform has to represent the full accelerations of the simulated vehicle and should drive the same trajectory ideally.

At first it was checked if there is a significant effect of the tire characteristics of solid tires on the MC performance compared to pneumatic tires. For this purpose, a “horizontal eight” maneuver at a target acceleration of 5 m/s² with solid and pneumatic tires is simulated. To investigate the influence of the slip angle correction algorithm on the MC performance for both tire types the simulation is done with active (dyn MC) and inactive (kin MC) slip angle correction. The lateral acceleration results of one turn of the horizontal eight are shown in time domain in Figure 9.

It is obvious that the slip angle correction of the MC improves the behavior for both types of tires. Especially the solid tire reaches only about 50% of the targeted lateral acceleration when slip angles are neglected in the MC algorithm. But also the pneumatic tire has an unacceptable high deviation when slip angles are not considered.

The results with activated slip angle correction show a high qualitative correlation to the target acceleration. The solid tire has a higher deviation which is caused by the nonlinearities of the lateral force characteristics. Figure 5 shows that a friction coefficient of 0.5, which is necessary for the targeted accelerations, results in slip angles of about 17° and is far out of the linear range of the shown characteristics. The linear approach of the
slip angle correction therefore calculates a lower slip angle to obtain the lateral force demand than would be necessary under consideration of nonlinearities. The pneumatic tire reaches a maximum slip angle of 4° which is still within the linear range of the tire characteristics.

Summarized it can be stated that the performance of the MC worsens at highly dynamic maneuvers if solid tires are used instead of pneumatic tires. A possible approach to improve the behavior is the consideration of nonlinearities in the slip angle correction based on the measurement data given in this work. Nevertheless, the shown highly dynamic maneuver is not a typical scenario for the WMDS. It has to be investigated if the shown behavior also holds for the typical application field of WMDS in urban traffic simulation.

### Vertical Dynamics

The performance of the WMDS concept is highly dependent on the quality of the used driving surface. Previous research only considered an ideal surface and neglected the vertical dynamics. To widen the application potential of the concept it is necessary to enable the use on uneven grounds of different quality. To approach that problem, the following working hypothesis is stated:

An ideal driving surface without unevenness is necessary for the application of WMDS without deterioration of the immersion of the subject.

Of course this consideration is theoretical because a driving surface without unevenness does not exist in reality but nevertheless it first has to be proven that even the smallest excitation is acceptable for an application of WMDS. The aim of the WMDS’ vertical dynamics research is to falsify this hypothesis. Therefore the current state of the simulator equipped with solid tires and a rigid connection between wheel and frame is assessed via computer simulation. Additionally, the potential of pneumatic tires for the improvement of the vertical dynamic behavior is analyzed.

### Research Tools

#### Road Model

The WMDS is an omnidirectional platform so that a single dimension road model is not sufficient. Therefore, a model based on a two dimensional inverse Fast Fourier Transform of a two-dimensional power spectral density is implemented, which is given in [Li15]. The resulting road excitation in longitudinal and lateral dimension is described with the power spectral density \( \Phi_h \) as a function of the angular frequency \( \Omega \) [Bra69]:

\[
\Phi_h(\Omega) = \Phi_h(\Omega_0) \left( \frac{\Omega}{\Omega_0} \right)^{-w}
\]

\( \Phi_h(\Omega_0) \) is the power spectral density at a reference spatial angular frequency \( \Omega_0 \) and describes the quality of a road. The waviness \( w \) is set to 2 which is a common value for the description of roads [Qua04].
Vertical Dynamics Model

The analytical vertical dynamics model consists of a rigid triangle frame with inertia properties in heave, pitch, and roll direction. The frame is mounted on three spring damper systems at the wheel positions representing the tire elasticity. The road excitation acts on the respective springs.

The implemented vertical tire model for both tires is a parallel spring damper system. The parameters of the solid tire are determined on a hydraulic shaker. A nonlinear elastic behavior is identified, which is modelled with a square polynomial of the tire deflection $\rho$ for the calculation of the spring force $F_{el}$:

$$F_{el} = k_2 \rho^2 + k_1 \rho$$  \hspace{1cm} (5)

The damper force $F_{damp}$ is modelled with a linear viscous approach:

$$F_{damp} = d_1 \dot{\rho}$$  \hspace{1cm} (6)

The determined parameters for the solid tire are given in Table 3 as well as the applied parameters of the pneumatic tire taken from [Pac12].

<table>
<thead>
<tr>
<th>Table 3 : Vertical tire model parameters</th>
<th>$k_1$ in N/mm</th>
<th>$k_2$ in N/mm$^2$</th>
<th>$d_1$ in Ns/mm</th>
<th>$N_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ST</td>
<td>486</td>
<td>83</td>
<td>0.51</td>
<td></td>
</tr>
<tr>
<td>PT</td>
<td>210</td>
<td>0</td>
<td>0.05</td>
<td></td>
</tr>
</tbody>
</table>

Simulation and Results

For the assessment of the vertical dynamic behavior of the WMDS the driven velocity profile has to be representative for a typical WMDS application. Therefore, an urban driving scenario is simulated with active MCA, TC, and washout.

As a reference for an achievable driving surface quality a class A road according to [ISO95] with a value $\phi_h(\Omega_0) = 1000 \text{ mm}^3$ is implemented as excitation. This corresponds to a new roadway layer of good roughness quality [Tya09].

The cumulative distribution of the occurring vertical accelerations with solid and pneumatic tires is shown in Figure 11. Additionally, a human perception threshold for accelerations of 0.2 m/s$^2$ is marked [Fog63]. For the application of the driving simulator on uneven grounds without additional deterioration of the immersion of the subject this threshold shall not be exceeded.

The results show that about 95 % of the occurring vertical accelerations during an urban simulation scenario exceed the perception threshold. This results mainly from the low damping generated by the tires. Though the value is similar for both tires the pneumatic tire shows a reduced occurrence of high accelerations compared to solid tires.

The question arises, which road surface quality is required for the application of WMDS which are solely sprung by tires and if it differs between solid and pneumatic tires. To investigate this question the road surface quality is increased iteratively by reducing the value $\phi_h(\Omega_0)$ until 99 % of the simulated vertical accelerations are below the perception threshold of 0.2 m/s$^2$. A low exceeding occurrence of 1 % is permitted to be less sensitive to single peaks. The determined necessary road qualities are shown as reference power spectral densities in Table 4. For a better quantitative rating of the surface quality the standard deviations of road heights are given as well.

| Table 4 : Required road qualities for the application of WMDS on uneven grounds |
|---------------------------------|-----------------|----------------|
|                                 | $\phi_h(\Omega_0)$ in mm$^3$ | Standard deviation of road height in mm |
| ST                              | 0.06            | 0.016          |
| PT                              | 0.28            | 0.033          |

Although the pneumatic tire requires a road of less quality than the solid tire a comparison between the required $\phi_h(\Omega_0)$ and the achievable values of a class A road shows a high quality difference. The standard deviation of the class A road simulated before amounts to 1.919 mm which is two orders of magnitude higher. To achieve the required quality a high construction effort compared to common roads would be necessary which reduces the flexibility of the concept. To avoid this, measures for the improvement of the vertical dynamic behavior are necessary.

The working hypothesis stated above is adjusted to the given results as a basis for the future research:

A driving surface with a reference spectral density of 0.28 mm$^3$ is necessary for the application of WMDS without deterioration of the immersion of the subject.
The aim of future research is the falsification of this hypothesis. Furthermore an enhancement of the vertical dynamics model is necessary. The previous considerations assumed a rigid force transmission between wheel and subject. Frame and seat elasticity as well as further damping elements possibly lead to lower surface requirements.

Conclusion and Outlook

The use of solid tires in WMDS promises advantages due to lower acceleration induced angular movements of the motion platform and a compact package compared to pneumatic tires. On the other hand, the identified solid tire characteristics show high nonlinearities and a low cornering stiffness, which results in negative impacts on the energy consumption and the motion control of WMDS.

An energy consumption increase of about 4 % was determined with urban traffic acceleration input signals for the simulator if solid tires are used.

It was shown that the nonlinearity of the solid tire leads to a five times higher lateral acceleration error of the motion control at high accelerations compared to pneumatic tires with a more linear behavior. Possible solution approaches, which have to be investigated in the future are nonlinear or closed loop control algorithms. Additionally, it has to be investigated if this influence is observable in urban traffic simulations with a low occurrence of high accelerations.

The investigation of the vertical dynamic behavior showed that both tires are not able to reduce the road induced oscillations acting on a subject to a suitable amount on a driving surface of a quality achievable with justifiable effort. Future research will address this problem. Concepts for the reduction of the subject’s immersion disturbance through road excitation have to be developed. Possible solutions which have to be analyzed are passive and active suspension systems known from vehicles but also the use of the hexapod for a vertical dynamics compensation is a possible approach.

References


