Model-Based Investigation of the Influence of Wheel Suspension Characteristics on Tire Wear

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Abstract. The amount of a vehicle's tire wear depends on several factors, such as material properties of the tire, environmental factors, driving behavior and especially the interaction between wheel suspension and wheel. While driving, the wheel has a defined setting to the road, which is given by the kinematic and compliance characteristics of the wheel suspension. This study takes an isolated look at wheel suspension characteristics with respect to tire wear. A flexible multibody simulation model of a multi-link rear axle is built up in MSC Adams/View to analyze the influence of wheel suspension parameters on the tire footprint. This model consists of a combination of flexible and rigid bodies and nonlinear connection elements like rubber metal bushings. The simulation model is enhanced by two FTire tire models, which is a widely used commercial physically based, 3D nonlinear flexible structure tire model. It was chosen because it has a separate tire tread model to compute the contact pressure and friction force distribution in the tire contact patch. To apply road excitation, a two-dimensional road model with a stochastic road profile is used. Various wheel suspension kinematics were set up and their influence on tire wear examined.

Keywords: Tire wear · Wheel suspension · Kinematics · Suspension model

1 Introduction

Due to the rapid increase in registered passenger cars in recent years and the related exploitation of fossil energy sources and environmental impact, new approaches to reduce resource consumption and environmental pollution are needed. Vehicle traffic constitutes a major source of dust, particulate matter, CO_2, NO_x, and other pollutant emissions [1, 2, and 3]. Furthermore, tire wear is the main source of microplastics, which play a major role of water body pollution [4]. Microplastics are often toxic to marine organisms, animals and even humans [5, 6]. While local exhaust emissions could be reduced by e-mobility, the dust or particulate matter emissions by tire wear remain unaffected [7]. As evident from Fig. 1, at least one quarter of dust emission is caused by tire wear. Moreover, tire wear consists of many other harmful chemical substances, which on the one hand is a source of environmental pollution and on the other hand as particulate matter can be inhaled by humans and can cause serious diseases [8, 9 and 10].

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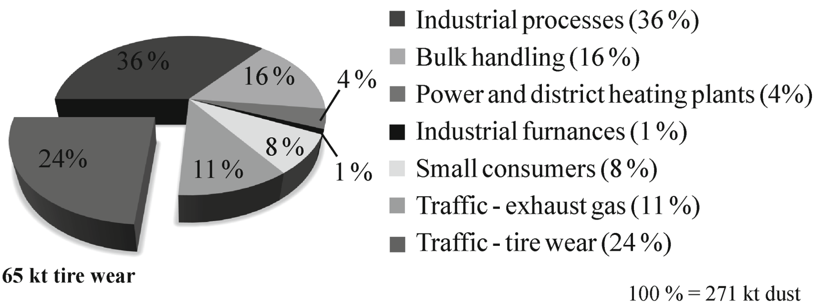

Fig. 1. Main causes of dust emission based on data of German Kraftfahrt-Bundesamt cited in [3]

Although not fully analyzed yet, it is certain that the sedimented dust is transported by air or rain to the environment. The detailed transportation process is subject of current research in Germany [11]. The percentage of microplastics due to tire wear lies between 28.3% and 38% [12]. In a study conducted by Fraunhofer Institute in 2018, it was found that tire wear constitutes the major source of microplastics in Germany [13]. Considering that the amount of tire wear depends on several factors, such as material properties of the tire, environmental factors, driving behavior and especially the interaction between wheel suspension and wheel [14], this paper focuses on model-based investigations of the influence of wheel suspension features on tire wear. This study takes an isolated look at one unsteered passenger car axle with its nonlinear characteristics and interactions between subsystems like wheel suspension, tire and road.

2 Wheel Suspension Characteristics

The vehicle axle with its two wheel suspension systems is one of the most important and complex vehicle systems. In combination with its wheels, it is the only connection between vehicle body and road. As a result, the wheel suspension system has great influence on the driving characteristics of the whole vehicle. It significantly affects driving dynamics, - safety and - comfort and has large impact on tire wear. Due to road excitations or dynamic vehicle motion, like pitch, roll or yaw, the tire is loaded by combined forces comprising vertical-, longitudinal and lateral loads. The transmission of longitudinal and lateral forces is characterized by friction in the tire contact patch and does not only depend on the amount of load, but especially on tires spatial position on the road [15].

A multilink wheel suspension system consists of three to five linkages, a spring, a shock absorber, several connecting elements such as rubber-metal bearings and other elements like spring plates. Due to the number of linkages and the position of linkage hardpoints (topology), during wheel travel (kinematics) the wheel performs a translational and rotational movement relative to vehicle body, [16, 17]. Owing to the elastic deformation of structural components and connecting elements (elastokinematics), the pure kinematics are superimposed by the suspension compliance characteristics. These elasticities change the kinematic movement of the wheel, depending on the magnitude and orientation of acting tire forces and moments [18]. The kinematic and elastokinematic wheel suspension characteristics are determined with a so-called Kinematics and Compliance (KnC) test rig, which is usually designed as full vehicle test rig. During test, the vehicle body is fixed on a movable test rig platform, which can bounce, roll and pitch. The tires or tire replacement systems are arranged on four separate ground plates. The ground plates represent the road and are all aligned in a horizontal plane. To analyze the kinematics of wheel travel the wheel pads are freely movable. Hence, for example toe, camber, track- and wheel base-changes can occur. For cornering, breaking or acceleration simulations, it is also possible to apply ground level forces at tire contact patch to analyze the suspension stiffness [19, 20]. At the Chair of Dynamics and Mechatronics at Paderborn University, a half-axle test rig to characterize wheel suspensions is available [21]. For parallel vertical wheel travel, the changes in wheel setting, that is for example toe, camber, and the movement of wheel contact point or wheel center, are measured relative to the vehicle coordinate system defined in ISO 8855. Typically, for rear wheel suspensions of passenger cars, the camber shifts to negative angle on bumping and to positive angle on rebound, which results in a negative gradient. In contrast, the toe angle changes to toe-in on bumping and to toe-out on rebound, yielding a positive gradient. This basic wheel suspension design is confirmed in [17, 22, and 23]. However, the gradient of toe and camber varies from car to car, as exemplarily shown in Fig. 2. The figure illustrates KnC-test results of quasi-static toe and camber change during parallel vertical wheel travel of different passenger cars. All curves were found by literature research (references in caption). To ensure better comparability, all vehicles were measured at curb weight and all curves are shifted by their static toe and camber angles, such that they cross the coordinate origin. So the figures only show the relative change in wheel setting.

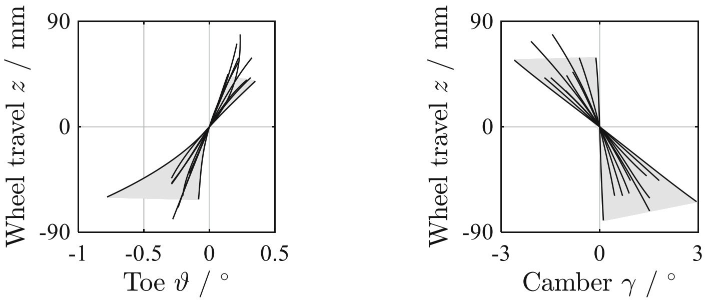

Fig. 2. Toe (left) and camber (right) angle changing during parallel vertical wheel travel of ten different rear axle systems [24, 25, 26, and 27]

Nevertheless, some passenger cars have different combinations of toe and camber gradients, for instance a combination of negative toe gradient with a negative camber gradient [16].

In addition to the gradients, the wheel contact point shifts in lateral and longitudinal direction. These changes of wheel setting not only have an impact on tires power transmission, but it also influences the friction between tire and road through the relative sliding movement in the tire contact patch. This is synonymous for the tire wear behavior.

3 Simulation Model

To analyze the influence of wheel suspension characteristics on tire wear, it is important to use a detailed simulation model which considers the nonlinear wheel suspension, wheel and road interactions [28, 29]. To this end, the simulation model is set up as a nonlinear flexible multibody system in MSC Adams/View, a widespread multibody simulation software. The model comprises a multi-link rear axle with two wheels and a road.

3.1 Rear Axle Model

As an axle model, an Audi self-tracking trapezoidal-link rear axle (Fig. 3 (left)) is chosen. It is an example for an actual multi-link wheel suspension concept for passenger cars from the mid-range segment. The trapezoidal links, wheel carriers, upper lateral control arms and tie rods are all made of aluminum. The spring and shock absorber are attached separately. The spring is located in front of the wheel center, and the shock absorber is located behind the wheel center and includes an additional progressive elastomer bump stop and a rebound stop. Both, the spring and the shock absorber, are mounted to wheel carrier and vehicle body. Between the left and right wheel suspension, a tubular anti-roll bar is installed. The steel subframe is mounted to the vehicle body by four rubber-metal bushings.

To represent rear axle compliance characteristics, the structural components of vehicle axle, like wheel carriers and linkages, are modeled as flexible bodies. This way the influence of component deformation and vibration behavior on wheel setting is considered during simulation. Furthermore, the anti-roll bar and its connection rods are also modeled as flexible bodies. To include component elasticity in multibody simulation, appropriate model reduction techniques had to be used. The used Craig-Bampton modal reduction method is explained in [30] and discussed in [31]. To connect two flexible bodies in Adams/View, it is necessary to add a dummy part between them. These dummy parts are used to model the mass of the bushing elements. The suspension bushing stiffness and damping features are modeled by general force components with Voigt-Kelvin-elements in each direction of all six degrees of freedom. They are parameterized with quasi static measured nonlinear spring characteristics and constant damping coefficients. The suspension spring has linear, the upper and lower spring plates nonlinear characteristics, same as the upper and lower damper mounts. Because of its high stiffness, the subframe is defined as a rigid body. The brake caliper is also considered as point mass, since its influence on unsprung mass and inertia. The vehicle body is also modeled as point mass and positioned at the vehicle's center of gravity height in the middle of the axle system in y_v-direction and on connection line between both wheels centered in x_v-direction. Because of the axle design, as a driven axle, the drive shafts are also taken into account. They are represented as assemblies of rigid bodies and ideal joints and are used to apply the drive torque to the wheel hub. The final multibody simulation model of the Audi rear axle system is shown in Fig. 3 (right). In summary it consists of 11 flexible bodies, 5 point masses, 31 rigid bodies and 36 ideal joints. This results in a complex simulation model with 222° of freedom.

Fig. 3. Audi self-tracking trapezoidal-link rear suspension: Real system (left) [32], Multibody simulation model in Adams/View (right)

After verifying the axle components on single component level, the entire rear axle system is verified and validated by comparing simulated KnC test data to experimental results, like exemplarily shown for vertical parallel wheel travel in Fig. 4.

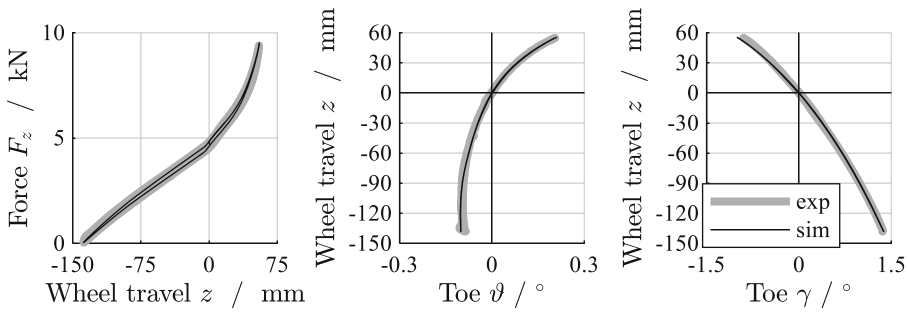

Fig. 4. Comparison of experimental and simulated KnC test results for vertical wheel travel

3.2 Tire and Road Model

As a tire model, a parameterized and validated physically based, 3D nonlinear flexible structure tire model (FTire) is used. Basically, FTire consists of two sub models, the structural model and the tread model. The structural model describes the tire's structural stiffness, damping and inertia properties. The tread model computes the contact pressure and friction force distribution in tire contact patch [33]. Furthermore, there are more model extensions, like a thermal or wear model, which are excluded in this study. The parameterization was done for the vehicle specific tire dimension and type.

To analyze the tire contact patch, the FTire tread model is used. It discretizes the tire contact patch with several contact elements. These contact elements are placed along parallel lines extending over the tread width. For each contact element i the contact forces (F_{fx}, F_{fy}) and sliding velocities (v_{sx}, v_{sy}) are calculated, if it is in contact with road. The sliding velocities are given in TYDEX-W. For the following calculation they are transformed into Adams inertial coordinate system. It is then possible to calculate the current frictional power for each contact element i at time t with

$$P_{f,i}(t) = \left|F_{fx,i}(t)v_{(sx,i)}\right| + \left|F_{fy,i}(t)v_{(sy,i)}\right|. \tag{1}$$

As a road model, a stochastic two-dimensional model from Adams library is used to generate road excitations with properties close to measured road profiles. The used road is defined in class C from DIN ISO 8608 which closely represents a national road in Germany [34].

4 Tire Wear

Tire wear depends on many different tire characteristics, for example the profile geometry, rubber compound of tread strip, vulcanization degree and normal pressure in contact patch, but is also affected by environmental conditions, like weather, ambient temperature, driving or road conditions [17]. The total friction force between tire and road composes of several different single component forces with the main components adhesion and hysteresis [35]. Hysteresis friction depends on the internal damping of a viscoelastic material due to deformation while sliding over a rough surface. In contrast, adhesion results from molecular bounds between contact partners. For viscoelastic materials like rubber, the friction coefficient depends on normal pressure, temperature and sliding velocity [36].

Because of high complexity of the tire wear process, a wide variety of empirical wear laws were established [36]. Fleischer used an energetic approach to describe the proportional relation between wear volume V_w and friction work W_f [37]

$$V_w = e_f^* W_f. \tag{2}$$

Based on this proportional relation, the frictional power from (1), which is friction work per time, is used to evaluate tire wear, in a qualitative manner.

5 Simulation and Results

To evaluate the influence of different wheel suspension characteristics on tire wear or friction work, the kinematics of wheel travel of the shown rear axle model were changed. As can be seen in Figs. 5 and 6, various toe and camber gradient settings were set up. To have an isolated view on toe and camber configurations, the angles were changed separately. For all simulations the initial wheel suspension settings like suspension rate or toe and camber angle in design position are identical. Because of the defined wheel load, the wheel travels approximate 20 mm compared Figs. 5 and 6.

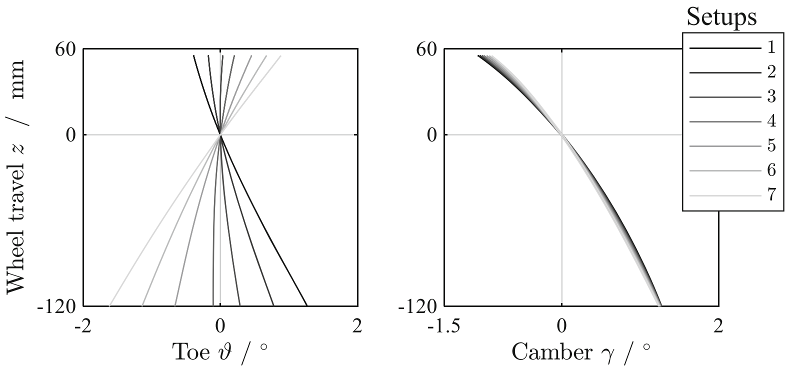

Fig. 5. Different wheel suspension setup's (setup 1–7) by changing toe gradient without changing camber gradient

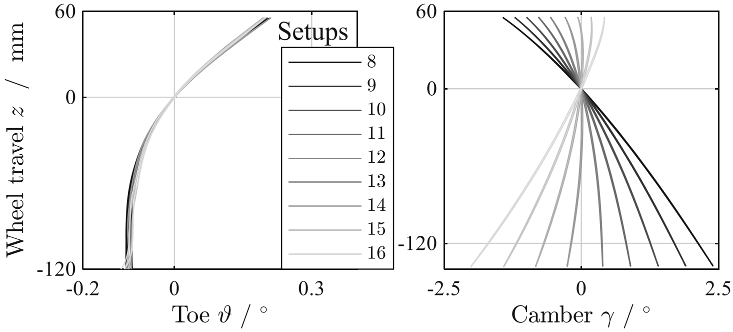

Fig. 6. Different wheel suspension setup's (setup 8–16) by changing camber gradient without changing toe gradient

For all of these 16 different wheel suspension setups, identical simulations with the above described road model were conducted. The axle model is mounted on ground, so that only translational movements in z_v and x_v direction and roll motion is possible. The axle systems velocity of translational motion on road is applied as rotational speed on each drive shaft. During simulation, the three different load cases, acceleration, uniform velocity of 100 km/h and retardation were considered. For the load cases acceleration and retardation the longitudinal acceleration amplitude is equal and always lower than 0,357 g, which is a good assumption for 95% of the drivers [38].

For evaluation of the influence of different wheel suspension settings on tire wear initially, for each contact element, the frictional power is calculated with (1). Afterwards the total current frictional power in the contact patch at time t is determined with

$$P_{f,j}(t) = \sum\nolimits_{i=1}^{n} P_{f,i}(t), \tag{3}$$

where n is the number of contact elements being in contact with the road. Due to the stochastic road excitations and dynamic nonlinearities of the entire system the frictional power or friction work should be analyzed in statistic mean related to distance or simulation time [39]. Because of the different load cases and hence varying distances to analyze, the specific friction Work W_f for simulation time period T is calculated with

$$W_f = \frac{T}{m} \sum\nolimits_{j=1}^{m} P_{f,\mathrm{j}}, \tag{4}$$

where m is the number of simulation output steps, which are taken into account. Finally, for better comparison, the results of (4) for each simulation load case and setup are normalized on the maximum value of W_f.

At first, in Fig. 7, the results for toe angle variation are presented. As can be seen for all load cases the maximal specific friction work for each load case is generated by setup 7, which has the largest positive toe gradient. For uniform velocity at 100 km/h and retardation the specific friction work decreases with the change to more negative toe gradient. For acceleration the overall changes are in total smaller and the results show a minimum for setup 5.

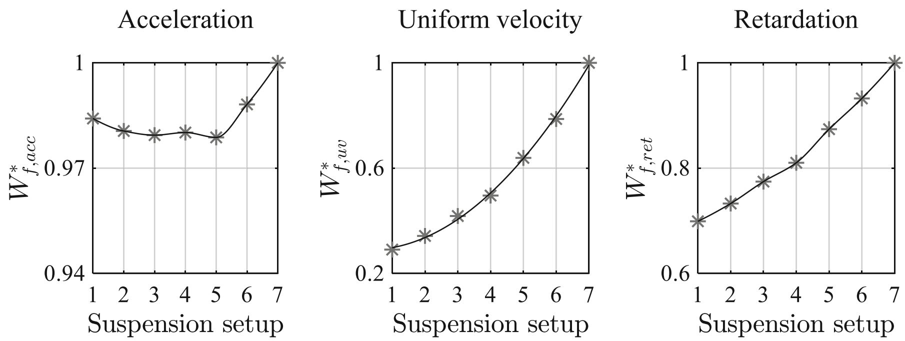

Fig. 7. Normalized specific friction work in tire contact patch for seven different toe angle gradients (setup 1–7) at the three different load cases, Acceleration (left), Uniform velocity (middle) and Retardation (right)

The simulation results from camber variation are shown in Fig. 8. In total it can be seen, that the influence of camber change on the specific friction work is less than from toe change. Most impact can be seen at uniform velocity. For all load cases a lower camber gradient leads to lower specific friction work.

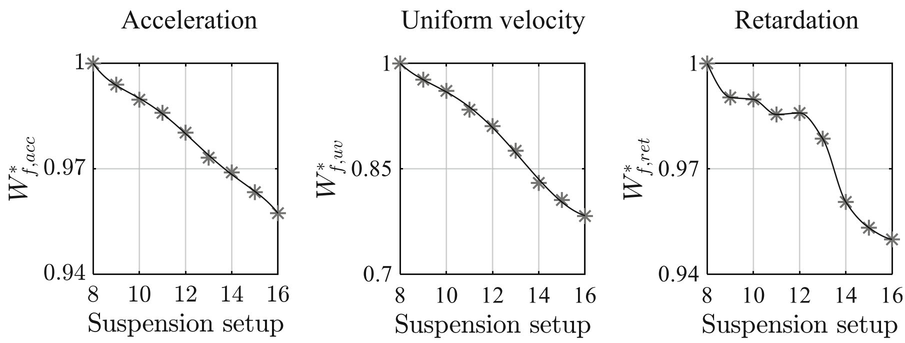

Fig. 8. Normalized specific friction work in tire contact patch for nine different camber angle gradients at the three different load cases Acceleration (left), Uniform velocity (middle) and Retardation (right)

6 Conclusion

In this paper a nonlinear flexible multibody simulation model, consisting of rear axle model, two FTire tire models and a road model was built up to analyze the influence of wheel suspension characteristics on tire wear. The friction work as a proportional physical parameter was used to evaluate the influence of wheel suspension settings on tire wear. The investigation shows, that with the presented approach driving simulations to analyze wheel suspension characteristics regarding tire wear can realized. The presented results point out great impact of toe angle and toe angle gradient on calculated specific friction work.

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References

1. Salb, C., Gül, S., Cuntz, C., Monschauer, Y., Weishäupl, J.: Klimaschutz in Zahlen. Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit (BMU), Berlin (2018)
2. Diegmann, V., Pfäffling, F., Wiegand, G., Wursthorn, H.: Maßnahmen zur Reduzierung von Feinstaub und Stickoxid. Umweltbundesamt, Dessau (2007)
3. Willeke, H.: CO2-Emission und Feinstaub in Verbindung mit Rollwiderstand von Reifen. DEKRA, Essen (2008)

4. Boucher, J., Friot, D.: Primary Microplastics in the Oceans: a Global Evaluation of Sources. IUCN, Schweiz, Gland (2017)
5. Carus, M.: (Mikro-)Plastik: Vom Werkstoff der unbegrenzten Möglichkeiten zum umweltgefährdenden Schadstoff?. nova-Institut, Hürth (2015)
6. Essel, R., Engel, L., Carus, M., Ahrens, R.H.: Quellen für Mikroplastik mit Relevanz für den Meeresschutz in Deutschland. Umweltbundesamt, Dessau-Roßlau (2015)
7. Timmers, V.R.J.H., Achten, P.A.J.: Non-exhaust PM emissions from electric vehicles. Atmos. Environ. **134**, 10–17 (2016)
8. Montague, P.: Tire dust. Rachel's Environ. Health Wkly **439** (1995)
9. UNECE: Particulate Matter Emissions by Tyres, Informal Document GRPE-65-20 (2013)
10. Avagyan, R.: Tire tread wear particles in ambient air - a previously unknown source of human exposure to the biocide 2-mercaptobenzothiazole. Environ. Sci. Pollut. Res. **21**, 11580–11586 (2014)
11. BMBF-RAU: Reifenabrieb in der Umwelt; BMBF research projekt (2017). https://bmbf-plastik.de/de/verbundprojekt/rau
12. Boucher, J., Friot, D.: Primary Microplastics in the Oceans – a Global Evaluation of Sources. International Union for Conservation of Nature, Gland (2017)
13. Bertling, J., Bertling, R., Hamann, L.: Kunstoffe in der Umwelt: Mikro- und Makroplastik, Ursachen, Mengen, Umweltschicksale, Wirkungen, Lösungsansätze, Empfehlungen, Kurzfassung der Konsortialstudie, Fraunhofer-Institut für Umwelt-, Sicherheits- und Energietechnik UMSICHT (Hrsg.), Oberhausen (2018)
14. Pottinger, M.G.: Contact Patch (Footprint) Phenomena, The Pneumatic Tire. NHTSA, Washington, D.C. (2006)
15. Albers, I.: Auslegungs- und Optimierungswerkzeuge für die effiziente Fahrwerkentwicklung, Aachen (2009)
16. Kohl, S., Zuber, A., Sextro, W.: Benteler Vehicle Dynamics – Fahrdynamikentwicklung basierend auf einer neuen Auslegungstheorie, Tag des Fahrwerks 2012, ika, Aachen (2012)
17. Heißing, B., Ersoy, M., Gies, S.: Fahrwerkhandbuch, 4. überarbeitete und ergänzte Auflage, Springer Vieweg Verlage, Wiesbaden (2013)
18. Kohl, S.: Modelbased investigations of gyroscopic effect on the (elasto-)kinematics of suspension systems. Proc. Appl. Math. Mech. **13**, 23–24 (2013)
19. Morsemeasurements (2019). www.morsemeasurements.com
20. AB Dynamics (2019). https://www.abdynamics.com
21. Schütte, J., Sextro, W., Kohl, S.: Halbachsprüfstand zur kinematischen, elastokinematischen und dynamischen Charakterisierung von Radaufhängungen, Fachtagung Mechatronik 2019 Paderborn (2019)
22. Reimpell, J.: Fahrwerktechnik: Grundlagen, 5. überarbeitete Auflage edn. Vogel Verlag, Würzburg (2005)
23. Matschinsky, W.: Radführungen der Straßenfahrzeuge. Springer Verlag, Berlin (2007)
24. Glaser, H., Rossié, T., Rüger, J., Conrad, T., Wagner, R.: Das Fahrwerk des Audi A1. ATZ Extra, Vieweg Verlag, Wiesbaden (2010)
25. Hudler, R., Leitner, W., Krome, H., Steigerwald, A., Fischer, S.: Die Achsen des neuen Audi A4. ATZ Extra, Vieweg Verlag, Wiesbaden (2007)
26. Rudolph, H.-J.: Audi Q3 – Entwicklung und Technik. Springer Vieweg, Wiesbaden (2013)
27. Hoffmann, J.: Potenziale einer aktiven Achskinematik zur Optimierung des Fahrverhaltens. Shaker Verlag, Aachen (2016)
28. Kohl, S., Sextro, W., Zuber, A.: Tire Footprint Analysis Depending on the Elastokinematics of a Multi-Link Suspension System Using Multi-Body Dynamics Simulation. PAMM, Wiley-VCH Verlag, Weinheim (2014)

29. Kohl, S., Sextro, W., Schulze, S.: Aspects of flexible viscoelastic suspension modeling for frictional rolling contact analysis using ADAMS. In: The 2nd International Conference on Automotive Innovation and Green Energy Vehicle, AiGEV 2016, Malaysia (2016, Preprint)
30. Craig, R.R., Bampton, M.C.: Coupling of Substructures for Dynamic Analyses, No. 6 (1968)
31. Schulze, S., Sextro, W., Kohl, S.: Using adequate reduced models for flexible multibody systems of automotive mechatronic systems. In: 2nd International Conference on Automotive Innovation and Green Energy Vehicle (AiGEV) Malaysia 2016 (2016, Preprint)
32. Audi Technology Portal (2019). www.audi-technology-portal.de
33. Gipser, M.: The FTire Tire Model Family, Esslingen (2010)
34. Braun, H.: Messergebnisse von Straßenunebenheiten, VDI-Bericht, Nr. 877 (1991)
35. Bachmann, T.: Literaturrecherche zum Reibwert zwischen Reifen und Fahrbahn, Fortschritt-Berichte VDI Reihe 12 Nr. 286, VDI Verlag, Düsseldorf (1996)
36. Moldenhauer, P.: Modellierung und Simulation der Dynamik und des Kontakts von Reifenprofilblöcken, Freiberg (2010)
37. Fleischer, G.: Energetische Methode der Bestimmung des Verschleißes, Schmierungstechnik 4, Nr. 9 (1973)
38. Mitschke, M., Wallentowitz, H.: Dynamik der Kraftfahrzeuge, 4 Auflage edn. Springer Verlag, Berlin, Heidelberg (2004)
39. Kohl, S.: Analyse der Reibleistungsverteilung im Reifenlatsch unter Berücksichtigung der Fahrwerkdynamik eines Mehrlenkerachssystems zur Bewertung des Reifenverschleißes, Dissertation, Schriften des Lehrstuhls für Dynamik und Mechatronik, Herausgeber: Prof. Dr.-Ing. habil. Walter Sextro, Paderborn, Universität Paderborn (2019)