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Vehicle Dynamics with RecurDyn Based on the TMeasy Tire Model

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Abstract: The analysis of critical driving maneuvers, the development of control systems, and the introduction of autonomous driving functions rely on virtual simulation environments. Vehicles are commonly modeled using multibody systems supported by commercial software that enables efficient setup, testing, and simulation. A functional vehicle model consists of rigid or flexible bodies, joints, and force elements. Passenger cars and trucks typically follow standardized model structures composed of predefined submodels such as drivetrain, steering, and suspension. Special-purpose vehicles, however, represent a much broader range of multibody systems, from simple rigid models to complex configurations with flexible components and moving contacts. The RecurDyn software package addresses this diversity and includes an integrated finite element solver, making it suitable for advanced vehicle simulations. In all cases, the vehicle model must be complemented by an appropriate tire model. Tire models are commonly divided into comfort and handling models. Comfort tire models are highly complex and require extensive measurements, while handling tire models use semi-physical approaches to approximate steady-state tire behavior with analytical functions and simplified dynamics. Most established handling models are tailored to passenger car tires. The TMeasy tire model, originally developed for agricultural tractor tires, uses physical parameters that can be derived from measurements or estimated by experienced engineers, which is especially beneficial when data are scarce. Its three-dimensional slip formulation ensures smooth transitions between standstill and motion. Combined with RecurDyn, TMeasy enables the simulation of a wide range of vehicles, particularly special-purpose vehicles with unconventional tires.

Keywords: multibody systems, rigid and flexible bodies, TMeasy tire model, finite elements, moving contacts

1. Introduction

Vehicle modeling by multibody systems is now standard in research and practice [1–4]. Commercial products, such as DYNA4 and CarMaker or TruckMaker, provide ready-to-use vehicle models based on generic multibody models. These models make use of the specific structure of passenger cars and trucks or tractor/trailer combinations. Adams/Car and the Simpack Automotive module enable engineers to swiftly build and test a wide range of vehicle models and subsystems. The focus is on cars, trucks, motorcycles, buses, and land machinery. Special-purpose vehicles are generally extremely different and cannot be assembled from a modular system consisting of predefined wheel/axle suspension templates or force elements. Virtual prototypes for special-purpose vehicles, such as a road roller, a forklift, or a straddle carrier, must be modeled from scratch. The setup of such models is time-consuming and can be done by hand or using a multipurpose multibody system package. Vehicles with rubber wheels require an appropriate tire model, which is not a standard feature of such software packages. The multi-flexible body dynamics implemented in RecurDyn is the most advanced tool available for simulating both rigid and flexible body dynamics. It combines traditional rigid multibody dynamics (MBD) with cutting-edge finite element technology for modeling flexible bodies. It also provides the General Tire Interface (GTire) interface, which allows the multi-body system model (MBS) to be completed with a tire model.

It is essential to take precise measurements to set up the model parameters for most tire models, including FTire, CDTire, MF-Tyre/MF-Swift, and UniTire. These measurements are performed on test rigs designed for passenger car tires, not special-purpose tires [5].

FTire and CDTire are complex structural tire models that address stability, handling, and the noise, vibration, harshness (NVH) domain [6]. Their application requires extensive tire measurements, which are generally not available for special-purpose tires.

The MF-Tyre/MF-Swift model can also be operated with a reduced and guessable parameter set. However, the user manual clearly states that this simplified application is restricted to typical passenger car tires and is therefore not applicable to the present task [7].

The UniTire model is clearly similar to the MF-Tyre model. It provides a tool that automatically derives the model parameters from measurements using regression techniques [8]. Applications to special-purpose tires are not reported.

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The study of Kim et al. [9] proposes a comprehensive analytical tire model for handling and ride comfort in the low frequency range, which is later known as the UA tire model. The study definitively states that its parameters are determined either experimentally or numerically by CAD software. It is important to emphasize that estimating the stiffness parameters is not straightforward. Tire models usually employ equivalent stiffness to approximate each physical element of a tire.

The UA tire model was recently enhanced by adding tire–road contact modeling for arbitrary uneven roads [10]. It copies the 4-point sampling of the TMeasy tire model. The analytical formulas of the UA tire model imply force discontinuities, which must be fixed by cubic smoothing functions as described in Millan and Ambrósio [11].

The TMeasy tire model uses smooth analytical formulas, allowing for simulations in all driving situations. It is based on a semi-physical approach involving a three-dimensional slip. With TMeasy, a skilled engineer can estimate tire model parameters. The tire size, estimated or measured payload, and tire–road friction coefficient provide the estimation basis, as documented in Gruber, and Sharp [12]. This unique feature enables TMeasy to be used with special-purpose tires, for which few or no measurements are usually available. Therefore, TMeasy was the obvious choice for this study.

All fundamental concepts of TMeasy can be found in Rill and Castro [13]. The publisher's website provides Matlab® files with applications of the TMeasy tire model. Appendices A and B list the Matlab® files that process vertical tire compliance measurements and compute steady-state tire characteristics using the TMeasy formula.

This paper uses the RecurDyn multibody system to model a compactor, a gantry crane, and a forklift. The model structures of these multibody systems differ significantly. The compactor can be modeled using a standard multibody system consisting entirely of rigid bodies. The focus here is on modeling the 3-point articulating joint, which enables the compactor to move on extremely rough surfaces.

Gantry frame compliance affects the lateral motion of the road contacts. This requires a flexible body approach. In this case, a modal reduction approach is sufficient.

The mast of a forklift is highly flexible and divided into parts. This requires a nonlinear flexible body modeling concept, which is also provided by the RecurDyn multibody system package. However, a practical vehicle model requires combining the multibody system with an appropriate tire model. The compactor and gantry crane have heavily loaded pneumatic tires, while the forklift has rather small super elastic tires. The specific features of the TMeasy tire model allow for applications not only for standard passenger car and truck tires but also for these types of special-purpose tires, as demonstrated in this paper. The GTire interface provided by RecurDyn couples the tire model TMeasy not only to rigid knuckles or axles but also to the flexible gantry crane frame.

2. TMeasy—an Easy-to-Use Tire Model

2.1. History and special features

TMeasy is a handling tire model based on a semi-physical approach. Vehicle simulations that are fast but still reliable require tire models, which provide a good compromise between accuracy and computation time [14]. TMeasy was developed to meet the urgent need for modeling the performance of large agricultural tractor tires on roads within an industrial project [15]. At the time, there were no measurements available for these tires. The first commercial TMeasy version was designed for use with passenger car and truck tires.

An improved version with a straightforward contact calculation was developed based on increasing experience from passenger car and truck applications. TMeasy uses a three-dimensional slip and applies a sophisticated but simple contact calculation as a standard. It is valid in all driving situations. A first-order tire dynamics system ensures a smooth transition from driving to standstill and vice versa. It also allows for the precise reproduction of parking torques [16]. The extended TMeasy version accounts for the in-plane longitudinal and rotational movements of the belt relative to the rim. The dynamics of the longitudinal force are of a higher order, which reproduces the wheel vibrations sufficiently well required for indirect tire pressure monitoring systems [17].

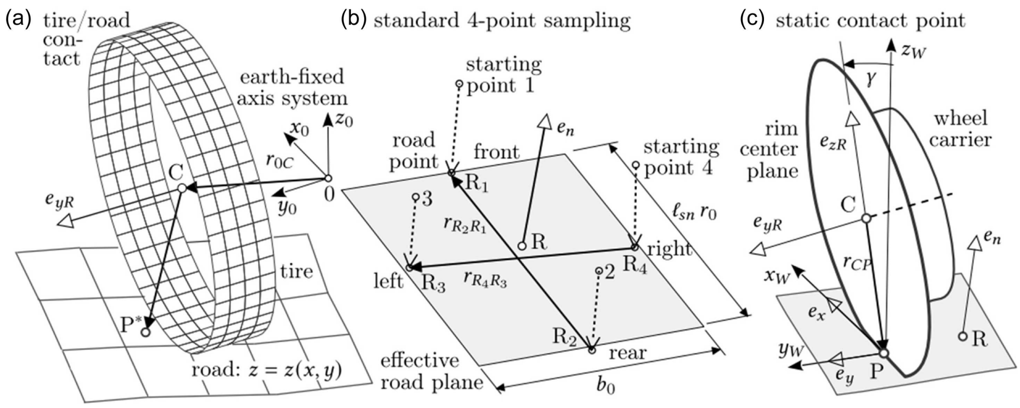
TMeasy's model parameters have a clear physical meaning, enabling engineers to make informed decisions even when limited data is available [12]. TMeasy does not require any initialization procedure. All TMeasy parameters can be changed on the fly. This allows for simulating a puncture and adapting TMeasy parameters to driving speed or tire temperature.

TMeasy is available in an ANSI C99 and a Fortran 90 version, and it can be integrated into any multibody system package with ease.

2.2. Tire–road contact

The vector r_{0C} and the unit vector e_{yR} define the position of the wheel center C and the direction of the wheel rotation axis with respect to an earth-fixed axis system (Figure 1a).

Figure 1
Standard contact calculation



TMeasy processes uneven roads. These roads are defined as two-dimensional functions that deliver the z-profile of the road and the μ-value of tire/road friction depending on the x and y-coordinates.

TMeasy uses a 4-point road sampling as a standard, which delivers an effective road plane defined by the road point R and the unit vector e_n normal to the effective road plane (Figure 1b).

The intersection of the rim center plane with the effective road plane yields the geometric contact point P, characterized by the shortest distance to the wheel center C, as well as the unit vectors e_x and e_y defining the longitudinal and lateral directions (Figure 1c). The tire camber angle directly affects the lateral position of the working point Q of the vertical tire force Fz (see Figure 2). The lateral shift y_Q, tire deflection Δz, and width w of the contact patch depend on the contact scenario (full or partial contact) and the tire's cross-section shape.

The TMeasy model uses a parabolic function to approximate the measured wheel load/tire deflection characteristics. This function is defined by its stiffness values at the payload and twice the payload. This allows us to estimate these parameters in the absence of measurements. The Matlab® script in Appendix A converts measurements to the corresponding TMeasy parameters using a least-squares approximation.

A roundness parameter in the range of $0 \le R_n \le 1$ combines the results for $R_n = 0$ and $R_n = 1$ to arbitrary rounded shapes of cross sections (Figure 2c). The working point Q of the vertical tire force defines the static contact point within TMeasy.

2.3. Steady-state tire characteristics

TMeasy modifies the slips resulting from a bristle model by the normalization parameters n_x and n_y and a small but positive fictitious velocity $v_N > 0$ (Figure 3). The fictitious velocity, added to the denominator, ensures that the longitudinal and lateral slips, s_x and s_y, remain finite even at vanishing wheel angular velocities, $\Omega = 0$. The term $r_D|\Omega|$ definitively describes the average velocity at which the tread particles are transported through the contact patch. The dynamic rolling radius, r_D, is modeled as a function of the vertical tire force. The terms v_x and v_y name the components of the contact point velocity in the longitudinal and lateral directions.

The steady-state tire characteristics in longitudinal and lateral directions are described as functions of the corresponding slips $F_x = F_x(s_x)$ and $F_y = F_y(s_y)$. The vector addition of slips s_x and s_y results in the combined slip s_c. This finally allows us to define a combined force characteristics $F_c = F_c(s_c)$. In TMeasy, each steady-state tire characteristic is defined by a set of physical parameters (see Figure 4). The initial inclination dF_y^0 in the lateral direction is also known as cornering stiffness.

An elliptic function transforms the parameters valid in the longitudinal and lateral directions to a corresponding set of parameters defining the combined force characteristics. The normalization parameters n_x and n_y used in TMeasy effectively compensate for the wide range of force characteristics in the longitudinal and lateral directions, automatically generating accurate approximations to measured combined forces [18]. Figure 3 defines the angle φ used here.

TMeasy specifies the parameters of the steady-state force characteristics at the payload and its double. This accounts for the impact of wheel load on tire characteristics, enabling straightforward parameter estimation. The Matlab® files in Appendix B clearly demonstrate how the TMeasy parameters of Figure 4 are processed to the steady-state characteristics and the combined force characteristics.

2.4. Tire forces and torques

The steady-state turn torque model uses a circle with a radius R_p to approximate the contact patch (see Figure 5). A pure turn motion with angular velocity ω_n about the patch normal results in a turn slip S_t. The term $R_t = (2/3)\ R_p$ represents the average turn radius, and the fictitious velocity $V_N > 0$ added to the denominator keeps the turn slip finite.

The turn slip S_t is now vectorially added to the combined slip S_c, which itself is composed of the longitudinal and the lateral slips S_x and S_y. The generalized and three-dimensional slip S_g characterizes the full sliding motion of the contact patch relative to the effective road plane. The combined force characteristics F_c, evaluated with the generalized slip S_g, result in the generalized force F_g. Decomposing this into its components gives the turn torque $T_z^{\ t}$ and the longitudinal and lateral forces F_x and F_y.

The global derivative $f_g = F_g/S_g$ is well defined even if $S_g = 0$. The TMeasy tire model performs extremely well even when the vehicle is at a standstill.

Figure 2
Lateral shift of contact point

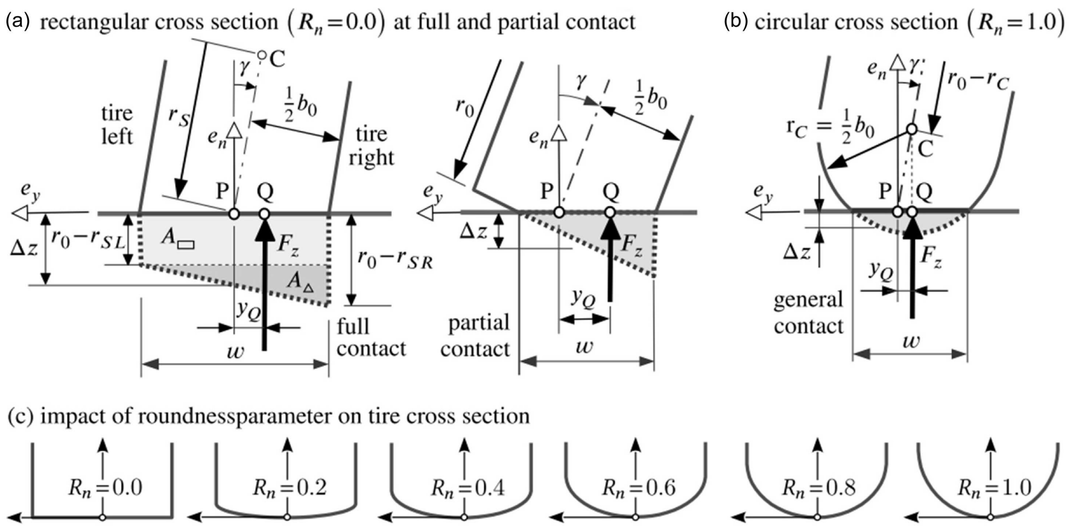


Figure 3
Slips and tire characteristics

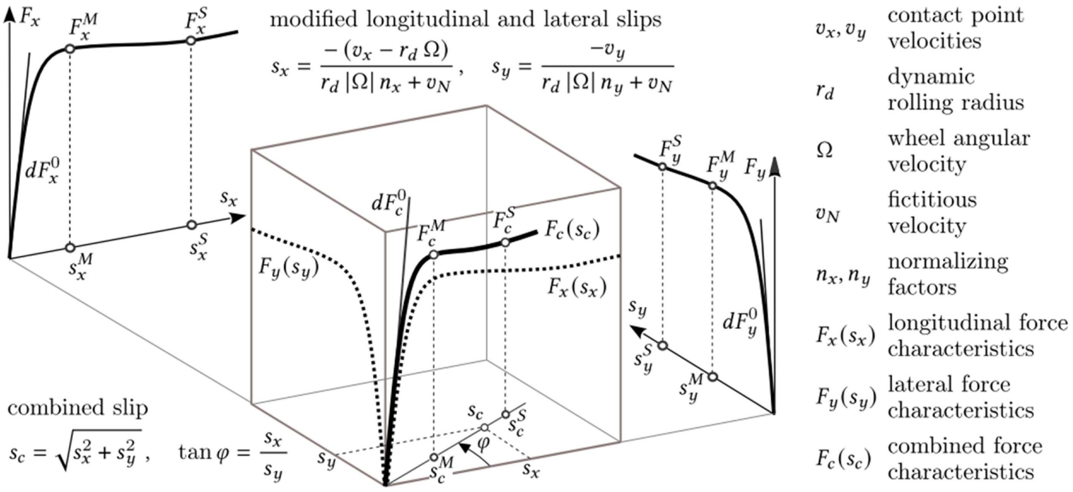


Figure 4
TMeasy parameters to define force characteristics

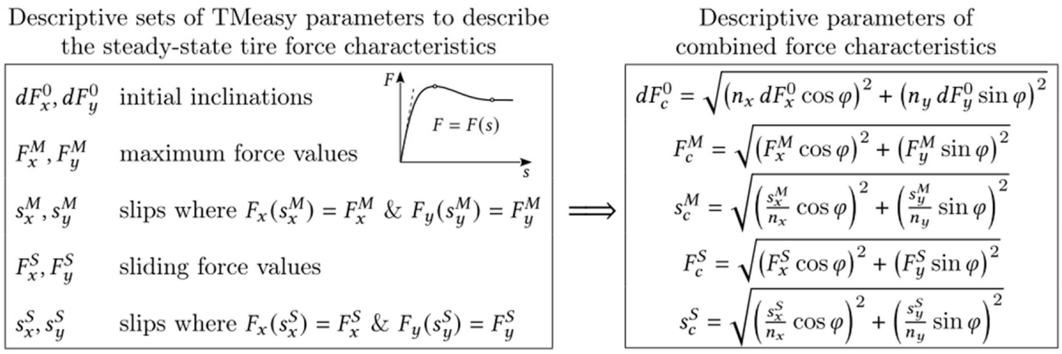
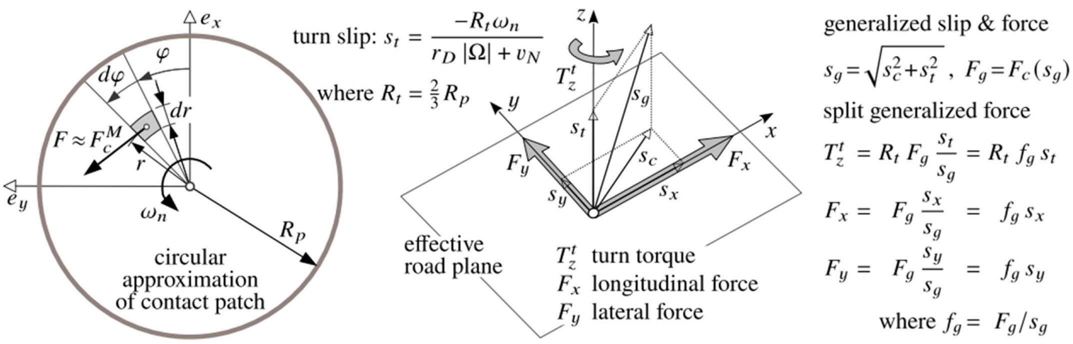


Figure 5
Turn torque and three-dimensional slip

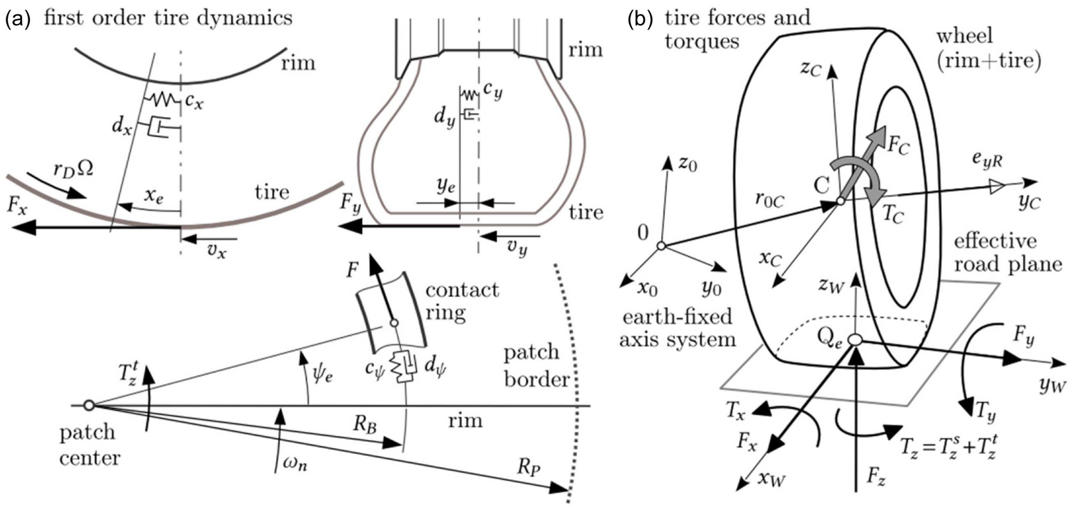


TMeasy applies a first-order dynamics for the longitudinal and lateral force as well as for the turn torque. It takes into account the tire deflections in circumferential, lateral, and torsional directions (Figure 6a). The time derivatives of the corresponding tire deflections x_e, y_e, and Ψ_e extend the sliding velocities used in the slips s_x, s_y, and s_t to $v_x + dx_e/dt$, $v_y + dy_e/dt$, and $\omega_n + d\Psi_e/dt$.

A Taylor expansion of the steady-state longitudinal and lateral tire forces and the turn torque, combined with the viscoelastic dynamic forces and turn torque, results in first-order nonlinear differential equations. These equations model the tire dynamics of TMeasy as a standard.

TMeasy models the vertical tire force F_z, or wheel load, as a nonlinear function of tire deflection and its time derivative. This is described in detail in Cheon et al. [19]. The turn torque T_x is already accounted for by the lateral shift of the contact point from the geometric to the static contact point Q. The dynamic contact point Q_e shown in Figure 6b also processes the tire deflections in the longitudinal and lateral directions. The rolling resistance torque T_y is modeled by an enhanced dry friction model. The

Figure 6
Tire forces and torques



torque about the vertical or normal direction consists of self-aligning and the turn torque $T_z = T_z^s + T_z^t$. The product of the tire offset n_y and the dynamic lateral force F_y provides the dynamic self-aligning torque $T_z^s = n_y F_y$.

The tire forces and torques are combined in the force vector F_c applied at the wheel/rim center C and the torque vector T_c.

2.5. The GTire interface

The GTire Interface in RecurDyn was developed for implementing tire models such as cosin/FTire or MF-Tire. It incorporates a first-order dynamic model to represent the interaction behavior within the interface. The interface was expanded in 2018 to meet the requirements of TMeasy. The TMeasy software and the MBD model are connected via the general force subroutine GTire_force (time, tid, wmid, rid, rrmid, sflag, jflag, iflag, tireforce). The TMeasy subroutine is called by the RecurDyn solver for each tire (tid) in the model at each solution time step (time). The subroutine returns the force vector F_c and the torque vector T_c for the tire force (tireforce) applied at the specified wheel coordinate system C (wmid) in the simulation model.

A new solver function, GRoad (rid, rrmid, cmdtype, roadpara, roadinf, iarray, carray, error), was developed. This function reliably returns the height (roadinfo) of a road surface point in the road reference system (rrmid) on the specified road data file (rid) for a given x,y road position (roadpara).

The implementation via a force subroutine allows the solver to calculate the resulting tire force at a discrete time step and to evaluate the system Jacobian by using a finite difference method. The jflag parameter in the GTire_force is set to 1 in that case, and it is set to zero otherwise. The TMeasy handling tire is handled like any other external force element during the RecurDyn solver run-time.

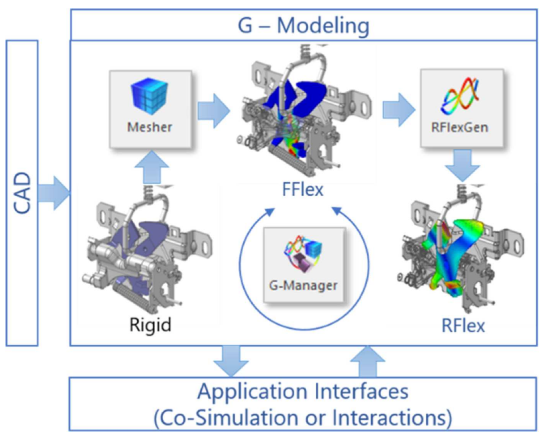
3. RecurDyn

3.1. Overview

RecurDyn is an excellent general-purpose MBD system on the market. It is designed for simulating mechanical systems with interconnected rigid or flexible bodies. The software package features a generalized body concept. In this concept, a selected body compliance (RIGID, RFLEX, or FFLEX) is regarded as a property of a generalized body (Figure 7). The user can switch between characteristics without having to redefine any connections, force elements, or contact definitions. RecurDyn's comprehensive suite of contact models, encompassing both general and analytical models, provides a robust framework for defining interactions between all three types of bodies, including self-contact. The contact algorithms are based on a penalty formulation.

RecurDyn is the clear choice for special types of complex applications like transmissions, tracked vehicles, conveyor systems, and more. The dedicated toolkits offer a broad library of predefined components. There are specific co-simulation capabilities. They have direct interfaces to particle-based CFD software, control system design tools, and other software supporting the FMI interface. RecurDyn's new simulation manager allows to set up and control a large number of simulations with different model parameter setups. Data-driven design techniques are supported by this, and MBD analysis results are integrated into companies' AI strategies.

Figure 7
G-modeling concept



3.2. Flexible bodies in RecurDyn

RecurDyn comprises two levels of flexibility for each body in a model. RFLEX bodies are flexible bodies based on the floating frame of reference formulation. They can undergo large reference displacements in 3D space but are limited to small body deformations. The flexibility is modeled using a linearization technique known as component mode synthesis. The flag of a body must be set to RFLEX. This means that the body degrees of freedom (DOF) include the translational and rotational DOFs of the body reference frame, as well as the amplitude of each deformation mode included in the model [20]. Rigid bodies must be analyzed with an appropriate eigenvalue analysis before switching to RFLEX. This analysis extracts the modes and eigenfrequencies of interest. You can do this directly in RecurDyn or using an external FEM software. Switching rigid bodies to flex bodies requires a finite element mesh of the body. You can import this mesh from external FEM software or generate it using the integrated Automesher option in RecurDyn.

The FFLEX body in RecurDyn is based on the incremental co-rotational formulation. This allows large body reference displacements with small finite element strain.

The formulation separates the overall motion of each element into two parts: the global rigid body motion of the undeformed element and the element deformation with respect to a local reference system (see Figure 8).

The position vector $\boldsymbol{r}^l$ and the 3 × 3 orientation matrix $\boldsymbol{A}^l$ of the reference frame are both functions of the global nodal position $\boldsymbol{q}_i$ of the nodes of the elements (Figure 9). The local nodal displacements $\boldsymbol{u}'^l_i$ are then defined by:

$$\mathbf{u}'^l_i = \begin{bmatrix} \mathbf{A}^{l\mathrm{T}}\,(\mathbf{q}_i - \mathbf{r}^l) - \mathbf{l}'^l_i \\ \Theta\,(\mathbf{A}^l \mathbf{A}^i \mathbf{C}^{li}) \end{bmatrix}$$

Figure 8
Co-rotational formulation

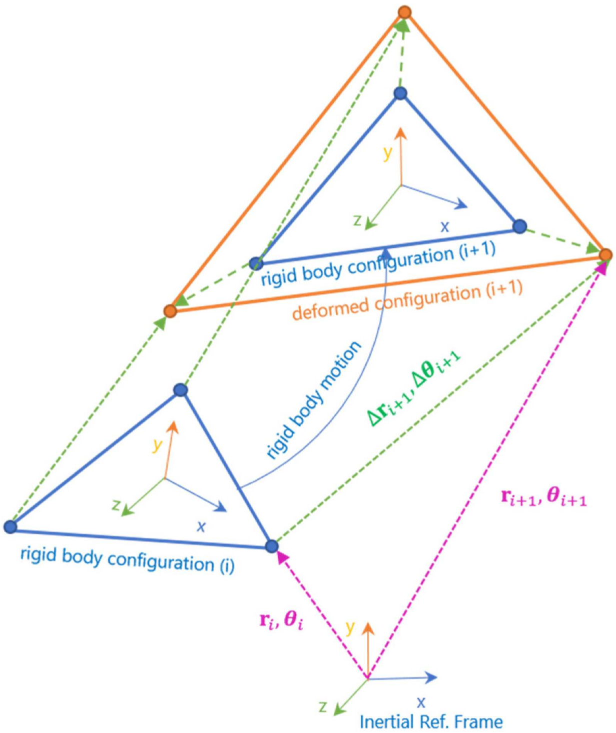
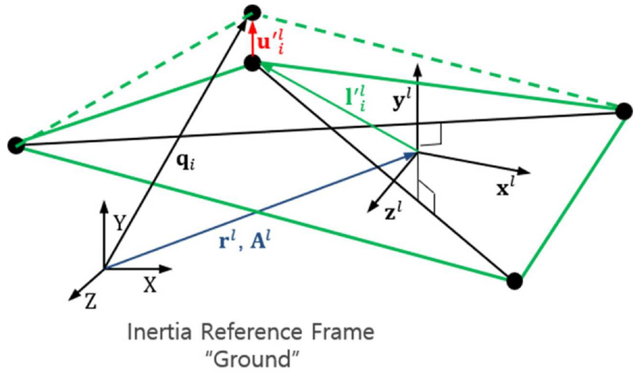


Figure 9
Definition of the nodal displacement vector



where Θ is a function which generates rotational displacements from $\boldsymbol{A}^l$ with the nodal orientation $\boldsymbol{A}^i$ and a constant orientation offset $\mathbf{C}^{li}$. Because the $\boldsymbol{u}'^l_i$ are local to the element reference frame, for small strain elements, the element stiffness matrices can be considered as constant. The stiffness matrices $\boldsymbol{K}'^l$, relative to the element reference frame, are formulated identically to a classical displacement-based finite element:

$$\mathbf{K}'^l = \int_V \mathbf{B}'^{\mathrm{T}} \mathbf{D} \mathbf{B}' \, dV$$

where $\boldsymbol{B}' = \hat{\varepsilon}'^l_{\boldsymbol{q}}$ is the vector of the partial derivatives of the element strain with respect to the element coordinates and $\boldsymbol{D}$ is the matrix of elastic moduli defining the strain to stress $\hat{\boldsymbol{\sigma}} = \mathbf{D}\hat{\boldsymbol{\varepsilon}}$ relationship. Finally, the equations of motion for a general system containing all three different kinds of bodies yield:

$$\mathbf{F} = \begin{bmatrix} \boldsymbol{M}\ddot{\boldsymbol{q}} + \boldsymbol{\Phi}_{\boldsymbol{q}}^T \lambda - \boldsymbol{Q} \\ \boldsymbol{\Phi} \end{bmatrix} = 0$$

where $\mathbf{F} = \mathbf{F}(\mathbf{q}, \dot{\boldsymbol{q}}, \ddot{\boldsymbol{q}}, \boldsymbol{\lambda})$ defines the system residual, which enforces Newton's second law, and $\boldsymbol{q}$ is the vector of the system degree of freedom, which includes the DOFs for the joint coordinates, the modal coordinates for RFLEX bodies, and the nodal translational and rotational DOF for the FFLEX bodies. $\boldsymbol{M}(\boldsymbol{q})$ denotes the system matrix, $\boldsymbol{\Phi}_{\boldsymbol{q}}(\mathbf{q})$ is the partial derivative of the constraints with respect to the DOFs, and λ is the vector of the Lagrange multipliers [21]. The vector $\boldsymbol{Q}(\dot{\boldsymbol{q}}, \ddot{\boldsymbol{q}})$ summarizes all forces acting on the bodies, which also includes the generalized dynamic force element that directly connects TMeasy to the RecurDyn solver.

If a simulation model uses FFLEX bodies, RecurDyn will use a Hybrid Integrator to solve the equations of motion. This integrator is based on an implicit single-step Newmark algorithm.

4. Application Examples

4.1. Compactor with smooth drum

The first application example for the interaction between RecurDyn and TMeasy is shown for the road/roller compactor HC 120i manufactured by Hamm AG (Figure 10).

The vehicle has an operational weight of 12.3[t] with a drum width of 2140 mm. The HC 120i's special steering system, based on a 3-point articulated joint (Figure 11), improves driving safety and comfort.

Figure 10
HC 120i compactor from HAMM AG

Figure 11
3-point articulated joint

The weight ratio of 56:44% between the front and rear axles results in a total wheel load of 5415 kg for the two rear tires of size 650/75 R32.

The simulation will determine the rolling results on a wavy road, largely determined by the road contact with the roller and the drive wheels. For this simulation scope, it is clear that all vehicle components can be modeled with a rigid body approach. This is because the local deformations of the compaction components are negligible and do not significantly influence the overall motion of the vehicle. We paid particular attention to a correct representation of the 3-point articulated joint, which is crucial for a realistic simulation of the entire vehicle movement.

The vehicle's low-pressure tires of the dimension AW 23. 1-26 12 PR are not standard tires, so the corresponding parameters are not easily accessible. From a methodological point of view, it is advisable to use the TMeasy handling tire model because the necessary tire parameters can be estimated by just taking the size, the payload, and the friction properties between the tire and the road into account.

This simulation model allows you to verify the proper function of the 3-point articulated joint (see Figure 12). The performance of the overall vehicle model is assessed by animated simulation results. Figure 13 shows the screenshot of a movie available at the RecurDyn website [https://www.functionbay.org/].

The experimental investigations also address the machine's climbing capability under defined road conditions. The mechanical interface between the road and the system is exclusively established via the roller and the tires. The frictional interaction between the tire and the road surface is a decisive parameter for this analysis. The tire model must reliably capture the relevant states of operation: rolling, sliding, and standstill. The test bench is configured as a quarter-circle setup, as shown in Figure 14. The numerical counterpart implemented in RecurDyn is shown in Figure 15 for direct comparison.

Figure 12
Motion of the 3-point articulated joint

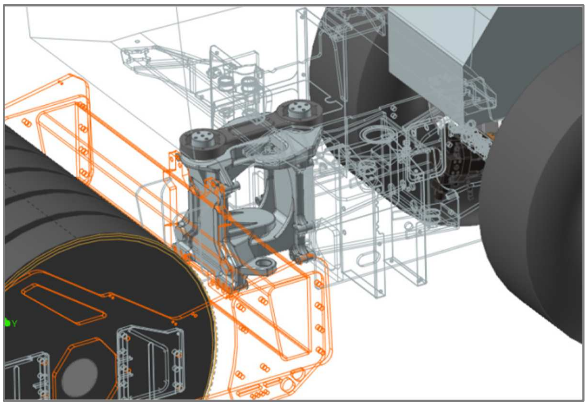


Figure 13
Simulation of the HC 120i on wavy roads

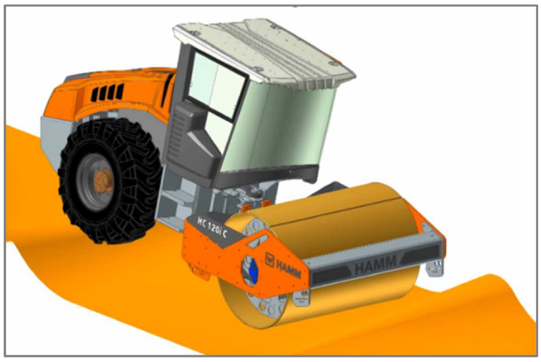


Figure 14
Test bench quarter circle

The combination of the simulation environment and tire model leads to a performant simulation model with accurate results compared to the real test results. Figure 16 shows the solver step size over simulation time for the complete maneuver. The step size fluctuates between 10 ms and 20 ms, which is a comparatively large value, indicating that the TMeasy tire model provides a smooth behavior at different driving velocities.

Figure 15
Test scenario in simulation environment

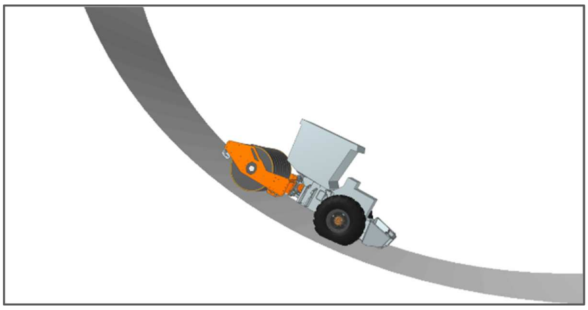


Figure 16
Solver step size over time

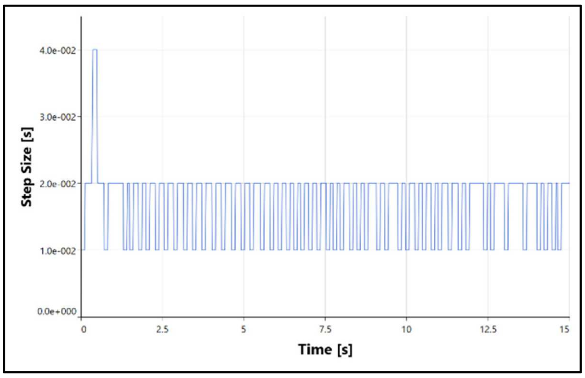
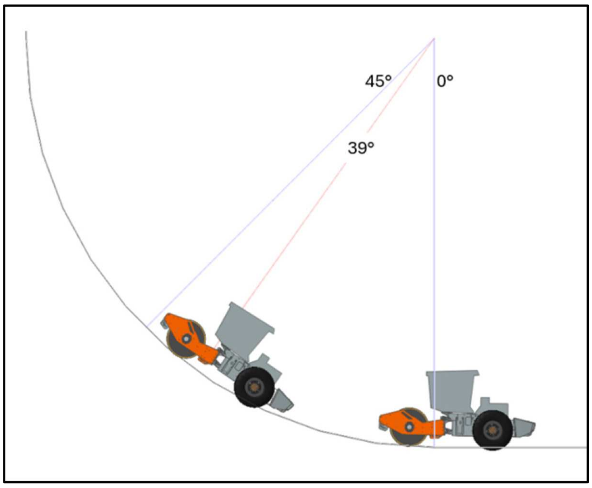


Figure 17
Simulation result of maximum angle

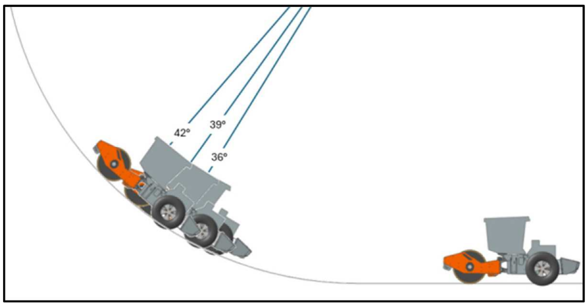


Achieving this goal requires the implementation of suitable integration methods. RecurDyn offers four different integration methods for this purpose. The model setup automatically selects and uses them. For the simulation of the compaction model, we used an implicit Generalized-Alpha integrator. This guarantees fast and reliable solutions for DAEs in multibody systems [22].

The corresponding test conducted under real road conditions yielded a maximum climbing angle of 39° for the applied machine configuration. This result was reproduced in the simulation (Figure 17).

Parameter studies were carried out to investigate the influence of the tire characteristics on the machine's climbing ability. For example, the maximum longitudinal tire force value $F_x{}^M$, as specified in Figure 4, was varied by 50% upward and downward, resulting in a change in the angle representing the climbing ability of ± 3° (Figure 18). By modifying individual parameters, the tire behavior can be directly analyzed without the necessity of reconstructing the entire characteristic map or conducting extensive parameter optimization studies. This represents a distinctive advantage of the TMeasy tire model for this kind of simulation task.

Figure 18
Climbing ability as a function of an individual tire parameter



4.2. Rubber-tired gantry train

The second example is the rubber-tired gantry crane RTG/CHARGER from KÜNZ GmbH (see Figure 19). The CHARGER product family is designed for wheeled operations in intermodal terminals with a lifting capacity up to 40.6 t and a maximum crane span up to 21 m. In this example, six tires of size 18.00 R25 were used.

Figure 19
KÜNZ RTG/CHARGER 01

The CHARGER does not move on rails but is equipped with several independent wheels on each side. The purpose of the simulation is to ensure that the track width is constant under all loading conditions. The track width is influenced by the bending stiffness of the frame when the payload is lifted. The tire rotation allows for additional lateral slip as soon as the CHARGER starts to travel. This is due to the lateral forces acting on the tires during the motion. To fulfill the simulation requirements, the crane's main structure must be modeled as flexible [23].

Figure 20
CHARGER simulation results

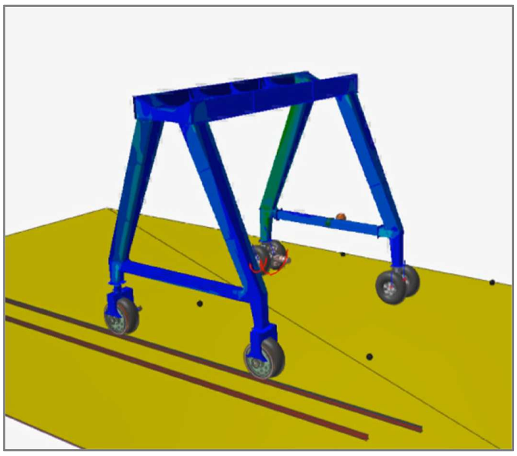


Figure 20 shows the corresponding model. A flexible body approach based on modal reduction (RD/RFLEX) is definitely sufficient in this case. The deformation of the frame can be considered small in relation to the overall dimensions of the frame structure. It is clear that the results depend significantly on the precise modeling of tire forces. The TMeasy handling tire is clearly the best choice. The related tire model parameter can be chosen with minimal effort by taking the basic tire properties into account.

The second requirement for the tire model is to deliver correct lateral forces at zero rotational speed. This unique feature of TMeasy for handling tires [17] is crucial for this type of application as the initial lateral forces acting on the tires start to ramp up before the crane starts to travel with the load.

4.3. Forklift

The last example is shown using the simulation of a forklift truck, in this case the STILL RX20-20 (Figure 21). The vehicle weighs 3.5 t when empty and can carry a maximum of 2 t. The RX20-20 is an electric front-wheel-drive forklift steered via the rear axle. It is equipped with super elastic tires of size 200/50-10 on the drive axle and with 150/75-8 on the steering axle. A finite element model of a forklift tire is quite elaborate. While it improves the analysis of complex loading conditions in industrial pavements and the impact of various rigid pavement parameters on load transfer, it requires hyperelastic material models and a falling weight deflectometer to validate relevant parameters [24].

Figure 21
STILL RX20-20 forklift truck

However, it does not necessarily improve road holding capacity, an important factor in this study. Therefore, TMeasy is also used here.

The manufacturer of the tire provided the wheel load/tire deflection characteristics, and Kion's measurements provided the tire stiffness properties in the longitudinal and lateral directions. The remaining TMeasy parameters were estimated and adjusted based on field measurements.

The main simulation target is to investigate the static and dynamic stability of the forklift by analyzing driving and braking performance, including tilting and rollover hazards with different loading conditions. The stability depends on the position of the center of gravity, which is significantly influenced by the mast deformation and tire compliance due to the loads applied at the fork twin. The simulation model includes flexible bodies for each of the three parts of the mast using RecurDyn FFLEX technology, while the chassis and the swinging rear axle are regarded as rigid for the scope of the simulation, as shown in Figure 22. The nonlinear finite element approach is clearly the best choice here, due to the contacts between the mast parts when the mast is continuously extended. TMeasy is the clear choice for modeling tires because it ensures the applied tire model delivers correct tire forces when the forklift is standing still. The tire properties can be estimated reasonably easily, as shown in the previous example.

Once the model setup is complete, the simulation environment allows the run of all tests specified in the DIN ISO 22915-2 directive. These tests verify the stability of counterbalanced trucks with masts, fork arms, or load handling attachments [25].

The combined model is undeniably robust despite its high structural complexity. The maximum solver step size varies only slightly depending on the driving situation (see Figure 23).

The flexible parts in this model require much smaller solver step sizes of about 1 ms compared to the road roller. The dynamics of the TMeasy model are well-matched by such small solver step sizes.

By controlling the resulting tire forces for each test, the user can validate if the criteria for a reliable and safe operation of the

Figure 22
Simulation model of the STILL RX20-20

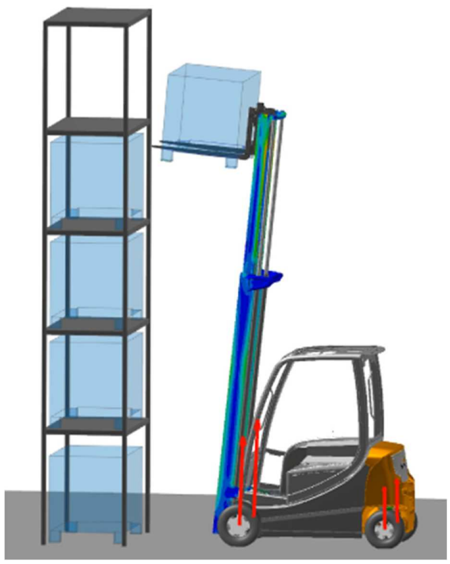
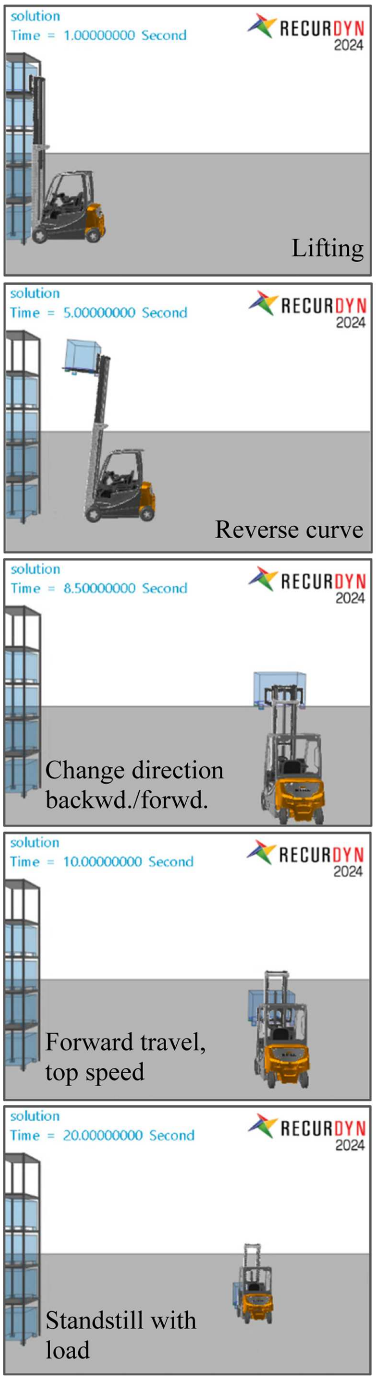


Figure 23
Driving situations and solver step size STILL RX20-20



TIME	STEPSIZE
7.184500E-01	1.250000E-03
8.384500E-01	6.250000E-04
1.040950E+00	1.250000E-03
1.243450E+00	1.250000E-03
1.397200E+00	1.250000E-03

TIME	STEPSIZE
4.658450E+00	1.250000E-03
4.804075E+00	1.250000E-03
4.946575E+00	1.250000E-03
5.124075E+00	1.250000E-03
5.310325E+00	2.500000E-03

TIME	STEPSIZE
8.492825E+00	6.250000E-04
8.570325E+00	1.250000E-03
8.665950E+00	6.250000E-04
8.727513E+00	1.250000E-03
8.843763E+00	1.250000E-03

TIME	STEPSIZE
9.955954E+00	1.000000E-03
9.993767E+00	5.000000E-04
1.008077E+01	1.000000E-03
1.018077E+01	1.000000E-03
1.028077E+01	1.000000E-03

TIME	STEPSIZE
1.998757E+01	1.250000E-03
1.999757E+01	1.250000E-03
2.000757E+01	1.250000E-03
2.001757E+01	1.250000E-03
2.002757E+01	1.250000E-03

current fork lifter design are met or if any kind of adjustment has to be performed.

5. Conclusion

Implementing handling tires in vehicle models in an MBD simulation environment is a common technique. In the past, it was difficult to achieve the necessary parameters for nonstandard tires, which are often used on special-purpose vehicles. This paper presents three typical applications of these kinds of vehicles. Using the handling tire TMeasy is clearly the best option in these cases. The tire parameters can be easily obtained by taking the size, the payload, and the friction properties between the tire and the road into account. TMeasy also supports zero tire rotational velocities. This is less important for passenger cars, but essential for special-purpose vehicles.

The RecurDyn tire interface GTire categorically considers TMeasy to be a generalized dynamic force element. The RecurDyn solver processes the tire dynamics. This ensures fast and reliable simulation results. The MBD model can comprise rigid bodies if component compliances of the vehicle are not significant or flexible bodies if the elastic characteristics are important. In the latter case, the user can choose between a linear approach based on the modal reduction technology (RD/RFLEX) or RD/FFLEX, which can take nonlinearities and contacts between those bodies into account.

Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

Data are available from the corresponding author upon reasonable request.

Author Contribution Statement

Uwe Eiselt: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Project administration. **Thomas Kelichhaus:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Writing – original draft, Writing – review & editing, Visualization. **Georg Rill:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization.

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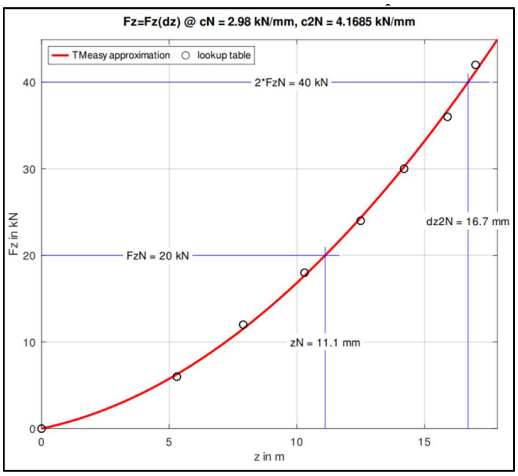
Appendix A

Matlab® script:

```
% Tire data sheet to TMeasy static wheel load Fz = Fz(dz)
clear, close all

% example for measured Fz in kN and tire deflection dz in mm
Fz = [0.0 6.0 12.0 18.0 24.0 30.0 36.0 42.0];
dz = [0.0 5.3 7.9 10.3 12.5 14.2 15.9 17.0];

FzN = 20; % set given or appropriate payload in kN

% least square aproximation by Fz = a1*dz + a2*dz2̂
a1 = (sum(Fz.*dz)*sum(dz.4̂) - sum(Fz.*dz.2̂)*sum(dz.3̂)) ...
/ (sum(dz.2̂)*sum(dz.4̂) - sum(dz.3̂)*sum(dz.3̂));

a2 = (sum(Fz.*dz.2̂)*sum(dz.2̂) - sum(Fz.*dz)*sum(dz.3̂)) ...
/ (sum(dz.2̂)*sum(dz.4̂) - sum(dz.3̂)*sum(dz.3̂));

% tire deflection and stiffness at Fz = FzN and Fz = 2*FzN
dzN = (-a1 + sqrt(a12̂ + 4*a2*FzN)) / (2*a2);
cN = (a1 + 2*a2*dzN); % stiffness at FzN in N/m
z2N = (-a1 + sqrt(a12̂ + 4*a2*2*FzN)) / (2*a2); %
c2N = (a1 + 2*a2*z2N); % stiffness at 2*FzN in N/m

% plot least square approximation and lookup table
dze = linspace(0,1,51)*1.05*max(dz);
Fze = a1*dze + a2*dze.2̂;
plot(dze,Fze,'r', 'Linewidth',2), hold on, grid on
plot(dz, Fz,'ok','Markersize',7,'Linewidth',1), axis tight

% add information
plot([0,1.05*dzN],[FzN,FzN],'b')
txt = ['FzN = ',num2str(FzN),' kN'];
text(0.3*dzN,FzN,txt, 'BackgroundColor','w')
plot([dzN,dzN],[0,1.05*FzN],'b')
txt = ['zN = ',num2str(dzN,3),' mm'];
text(dzN,0.5*FzN,txt,'BackgroundColor','w' ...
,'HorizontalAlignment','center')

plot([0,1.05*z2N],2*[FzN,FzN],'b')
txt = ['2*FzN = ',num2str(2*FzN),' kN'];
text(0.5*z2N,2*FzN,txt,'BackgroundColor','w')
plot([z2N,z2N],[0,2.05*FzN],'b')
txt = ['dz2N = ',num2str(z2N,3),' mm'];
```

Figure 1
Vertical tire force vs. deflection comparison



```
text(z2N,1.2*FzN,txt,’BackgroundColor’,’w’ ...
,’HorizontalAlignment’,’center’)

xlabel(‘z in m’), ylabel(‘Fz in kN’)
title([‘Fz = Fz(dz) @ cN = ‘,num2str(cN,5),’ kN/mm, ‘ ...
,’c2N = ‘,num2str(c2N,5),’ kN/mm’])

legend(‘TMeasy approximation’,’lookup table’ ...
,’location’,’NorthWest’,’orientation’,’horizontal’)
```

Appendix B

Matlab® script: steady_state_tire_chars.m

```
% TMeasy steady state tire characteristics with
% special purpose tire parameters estimated and rounded
clear, close all

% unloaded radius, payload, vertical stiffness
r0 = 0.8200; fz0 = 140000; cz = 2750000;

% tire characteristics in long. and lat. directions
dfx0 = 1700000; dfy0 = 970000; % init slopes in N/-
fxm = 115000; fym = 105000; % maximum forces in N
sxm = 0.250; sym = 0.320; % sm where f(sm) = fm
fxs = 110000; fys = 104000; % sliding forces in N
sxs = 0.500; sys = 0.700; % ss where f(ss) = fs

% dynamic tire offset parameter
n0 = 0.140; % normalized tire offset n/L @ sy = 0
sy0 = 0.400; % sy where n/L passes sy-axis
syE = 0.550; % sy where n/L approaches sy-axis again

% compute slip normalizing factors
hsxn = sxm/(sxm+sym) + (fxm/dfx0)/(fxm/dfx0+fym/dfy0);
hsyn = sym/(sxm+sym) + (fym/dfy0)/(fxm/dfx0+fym/dfy0);

nvar = 101; % generate various slip values
sx = linspace(-1,1,nvar)*1.1*max(sxs);
sy = linspace(-1,1,nvar)*1.1*max(sys);
% pre-allocate fx, fy and ts to speed up loop
fx = zeros(length(sx),length(sy)); fy = fx; ts = fx;

% tire forces, tire offset, and self-align. torque
L = 2*sqrt(r0*fz0/cz); % estimated contact length
for j = 1:nvar
   to = L*tmy_tireoff(sy(j), n0,sy0,syE);
   syn = sy(j)/hsyn;
   for i = 1:nvar
     % combined slip
     sxn = sx(i)/hsxn;
     sc = sqrt (sxn^2 + syn^2);
     if sc > 0
       cphi = sxn/sc; sphi = syn/sc;
     else
       cphi = sqrt(2)/2; sphi = sqrt(2)/2;
     end
     % combined characteristic for normalized slip values
     df0 = sqrt((dfx0*hsxn*cphi)^2 + (dfy0*hsyn*sphi)^2);
     fm = sqrt((fxm*cphi)^2 + (fym*sphi)^2);
     sm = sqrt((sxm/hsxn*cphi)^2 + (sym/hsyn*sphi)^2);
     fs = sqrt((fxs*cphi)^2 + (fys*sphi)^2);
```

```
        ss = sqrt((sxs/hsxn*cphi)2̂ + (sys/hsyn*sphi)2̂);
        % combined tire force
        [f, ~] = tmy_fcombined(sc, df0,fm,sm,fs,ss);
        % split into longitudinal and lateral forces
        fx(i,j) = f*cphi; fy(i,j) = f*sphi;
        % self-aligning torque
        ts(i,j) = -to*fy(i,j);
    end
end

fx = fx/1000; fy = fy/1000; ts = ts/1000; % N –> kN
subplot(2,2,1); ir = 1:2:nvar; % reduced samples
plot(fx(:,ir),fy(:,ir),'k','LineWidth',1), hold on
plot(fx(ir,:).',fy(ir,:).','k','LineWidth',1), grid on
xlabel('f_x/kN'), ylabel('f_y/kN')
title('combined force'), axis equal

is = round((nvar + 1)/2):10:nvar; % selected slips only
subplot(2,2,2); plot(sy,ts(is,:).','LineWidth',1)
xlabel('s_y'), ylabel('kNm')
title('self-aligning torque @ selected s_x'), grid on
legend(num2str(sx(is).'),'location','southeast')
subplot(2,2,3); plot(sx,fx(:,is),'LineWidth',1)
xlabel('s_x'), ylabel('kN')
title('f_x = f_x(s_x) @ selected s_y'), grid on
legend(num2str(sy(is).'),'location','southeast')
subplot(2,2,4); plot(sy,fy(is,:).','LineWidth',1)
xlabel('s_y'), ylabel('kN')
title('f_y = f_y(s_y) @ selected s_x'), grid on
legend(num2str(sx(is).'),'location','southeast')
```

Matlab® function: tmy_fcombined.m

```
function [f, fos] = tmy_fcombined ... % combined force
(s ... % generalized slip
, df0 ... % initial inclination of gen. force char.
, fm ... % maximum force value
, sm ... % slip where f(sm) = fm
, fs ... % sliding force value
, ss) % slip where f(ss) = fs

% defaults (df0 = 0, s = 0)
f = 0.0; fos = df0;

% adjust smloc and ssloc if df0 is too small
    if df0 > 0.0
        smloc = max([2.0*fm/df0, sm]);
        ssloc = ss + (smloc-sm);
    else
        return;
    end

% normal operating conditions
    if s > 0.0 && smloc > 0.0
        if s > ssloc
            % full sliding
            f = fs;
            fos = f/s;
        else
            if s < smloc && fm > 0.0 % adhesion
                p = df0*smloc/fm - 2.0;
                sn = s/smloc;
                fos = df0 / (1.0 + (sn + p) * sn);
                f = fos * s;
```

```
        else % adhesion –> sliding
          a = (fm/smloc)*(fm/smloc) / (df0*smloc);
          sstar = smloc + (fm - fs)/(a*(ssloc - smloc));
          if sstar <= ss
            if s <= sstar
              f = fm - a*(s - smloc)*(s - smloc);
            else
              b = a*(sstar - smloc)/(ssloc - sstar);
              f = fs + b*(ssloc - s)*(ssloc - s);
            end
          else % one cubic function (just in case)
            sn = (s - smloc)/(ssloc - smloc);
            f = fm - (fm - fs) * sn*sn *(3.0 - 2.0*sn);
          end
          fos = f/s; % global derivative
        end
      end
end
end
```

Matlab® function: tmy_tireoff.m

```
 function n2L = tmy_tireoff ... % normalized tire offset
(sy ... % lateral slip
, n2L0 ... % normalized caster offset n/L @ sy = 0
, sy0 ... % lateral slip where n/L passes sy-axis
, syE) % lateral slip where full sliding starts

sya = abs(sy); % absolute value because n(sy) = n(-sy)
   if sya < syE % 4th-order polynomial
      a = -(2*sy02̂ + (sy0 + syE)2̂); % coefficients
      b = (2*(sy0 + syE)2̂) / syE; % normalized to
      c = -(2*sy0 + syE) / syE; % (sy0*syE)2̂
      n2L = n2L0*(1 + (sya/(sy0*syE))2̂*(a + sya*(b + sya*c)));
   else
      n2L = 0; % full sliding
   end
end
```

Figure 2
TMeasy tire characteristics