

User Tire Road Model and Road Sensor for Advanced Vehicle Dynamic Applications

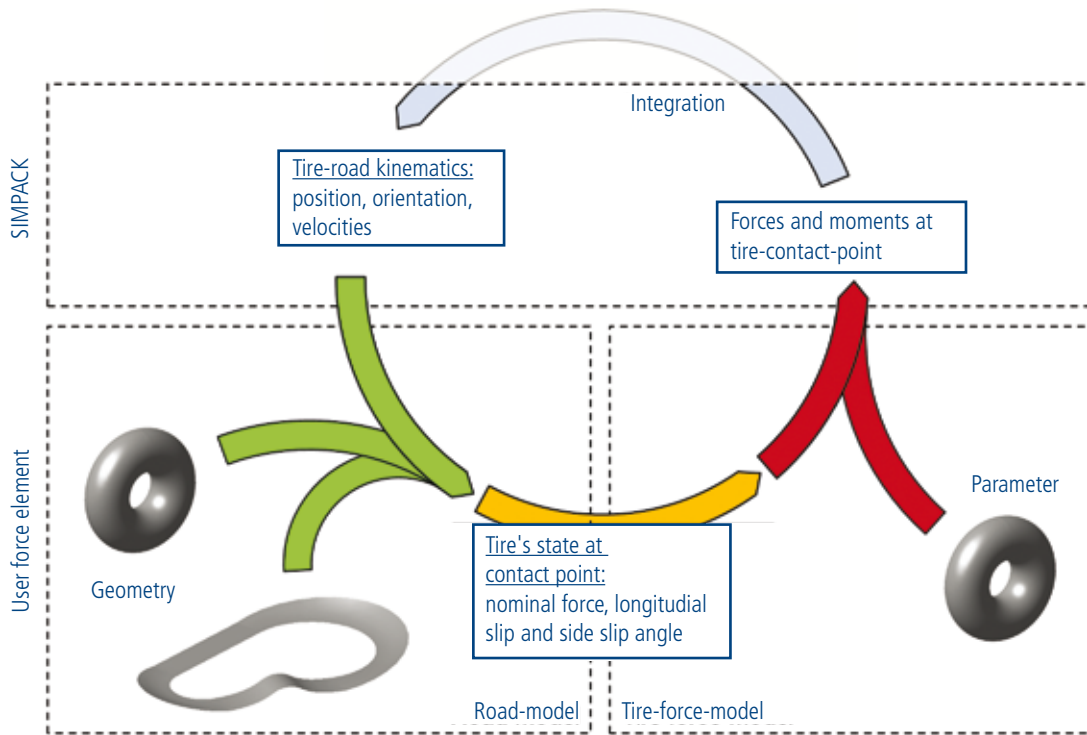


Fig. 1: Tire-road modeling



The mathematical description of a road surface within multi-body simulation is a major factor in simulation error, simulation time and modeling possibilities. For advanced vehicle dynamic applications, a new road-description method has been introduced. The method uses relative kinematics to enable test rig simulations with moveable road surfaces described by an abstract NURBS surface. This allows an exceptional level of detail [1, 2]. Implementation of NURBS surface for vehicle dynamic simulation also includes an optimized algorithm for contact point determination to calculate a tire's state. As shown in Fig. 1, the main aspect of

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the new user tire road model is the road modeling part. Different existing tire force models (e.g., HSRI, Pacejka Magic Formula) are implemented by using a universal interface for single contact point tire force models.

ROAD SURFACE DESCRIPTION

With the new user tire road model, the road is modeled in SIMPACK as a rigid body which does not need to be equal to the inertia frame. The user has to specify a body marker as a reference system for the road surface used in the tire road force element. The road surface is described as a non-uniform rational B-splines surface (NURBS) [3] to enable the most efficient simulation progress. NURBS surfaces uses a recursive algorithm to calculate a surface point S depending on the surface coordinates u and v by considering interpolation points $P_{i,j}$ and knot vectors U and V (including the interpolation order p, q and q), see Fig. 2. NURBS surfaces

are only valid within the limits $[u_{min}, u_{max}]$ and $[v_{min}, v_{max}]$.

$$(1) S(u, v) = \frac{\sum_{i=0}^n \sum_{j=0}^m N_{i,p}(u) N_{j,q}(v) w_{i,j} P_{i,j}}{\sum_{i=0}^n \sum_{j=0}^m N_{i,p}(u) N_{j,q}(v) w_{i,j}}$$

$$(2) N_{i,0} = \begin{cases} 1 & \text{if } U_i \leq u < U_{i+1} \\ 0 & \text{otherwise} \end{cases}$$

$$(3) N_{i,p} = \frac{u - U_i}{U_{i+p} - U_i} N_{i,p-1}(u) + \frac{U_{i+p+1} - u}{U_{i+p+1} - U_{i+1}} N_{i+1,p-1}(u)$$

$$(4) U = \{ \underbrace{u_{min}, \dots, u_{min}}_{p+1}, U_{p+1}, \dots, U_n, \underbrace{u_{max}, \dots, u_{max}}_{p+1} \}$$

$$(5) V = \{ \underbrace{v_{min}, \dots, v_{min}}_{q+1}, V_{q+1}, \dots, V_m, \underbrace{v_{max}, \dots, v_{max}}_{q+1} \}$$

The NURBS interpolation method also enables the calculation of the surface derivatives at u and v : $\delta S(u, v)/\delta u$, $\delta S(u, v)/\delta v$.

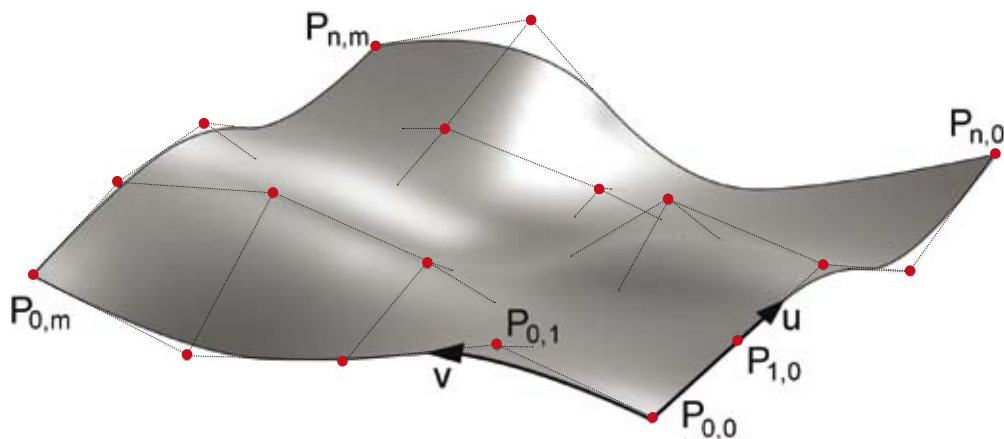


Fig. 2: NURBS surface

The first derivatives are used to calculate the normal vector on a surface point in a right handed system and to perform an iteration process to determine the tire road contact point as described below.

The advantages of a NURBS surface method are:

- A free definition of the interpolation order in both surface directions (e.g., linear interpolation in the lateral direction and second order interpolation in the longitudinal road direction).
- Every linear interpolated surface can be identically represented by the NURBS interpolation method (e.g., OpenCRG data).
- Increasing the interpolation order removes unwanted surface kinks and allows the user to reduce the number of interpolation points (e.g., a roller drum test bench or an arbitrarily sized circle can be represented by a NURBS surface with only 14 interpolation points, see Fig. 3).

- By calculating the surface points derivatives without a lot of additional effort, fast contact point calculation routines can be developed.
- A NURBS surface can represent all dimensions. For the road model, four dimensions are defined: the three-dimensional position x, y and z and also the friction coefficient μ .

CONTACT POINT CALCULATION

The contact point $S(u, v)$ is defined as the surface point which has the greatest intersection into a rigid wheel volume (represented by a torus, defined by two parameters: outer diameter d_w and width w_w).

The contact point is found using an advanced iteration method based on a simple concept (see also Fig. 4):

During the simulation process, the contact point is continuously moving on the road surface. The contact point which was calculated at the last time step is close to the current contact point. The iteration process to find the new contact point is performed

by calculating the surface point S_k and the orientation matrix A_k at the starting values u_k, v_k :

$$(6) A_k = \begin{bmatrix} \frac{\partial S}{\partial u} & \frac{\partial S}{\partial v} & \left(\frac{\partial S}{\partial u} \times \frac{\partial S}{\partial v} \right) / \left| \frac{\partial S}{\partial u} \times \frac{\partial S}{\partial v} \right| \end{bmatrix}$$

Using the normal vector $A_{k,z}$, the current "deepest" point C on the wheel (W) torus volume can be calculated:

$$(7) \overline{WC} = \vec{q} \cdot \frac{(d_w - w_w)}{2} - A_{k,z} \cdot \frac{w_w}{2}$$

$$(8) \vec{q} = \frac{A_{w,y} \times (A_{w,y} \times A_{k,z})}{|A_{w,y} \times (A_{w,y} \times A_{k,z})|}$$

Adopting the column vectors of A_k which are linearly independent, and given that the change of A_k is small, the modification of u_k, v_k results in:

$$(9) [\Delta u \quad \Delta v \quad \Delta z]' = A_k^{-1} \cdot \overline{S_k C}$$

$$(10) u_{k+1} = u_k + \Delta u, \quad v_{k+1} = v_k + \Delta v$$

Practical usage of this iteration process showed that two additional cases must be considered:

- Finding the values u_0, v_0 at start of simulation.
- Handling discontinuity in the surface derivatives.

Both problems can be solved by considering the knot vectors U and V . Because discontinuity only appears on knot vectors elements (see formula 2-5), a global search of the

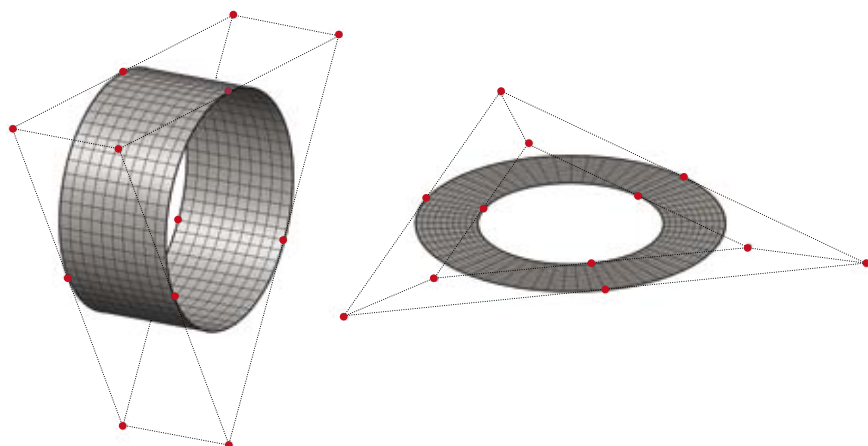


Fig. 3: Reduced number of interpolation points

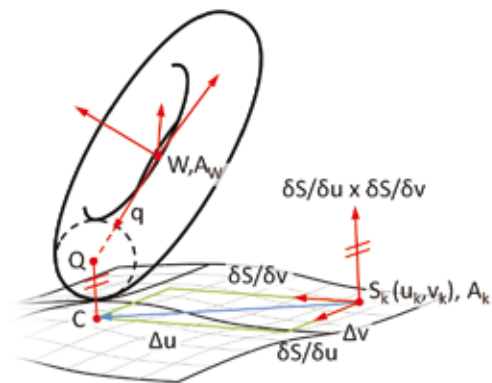


Fig. 4: Contact point iteration

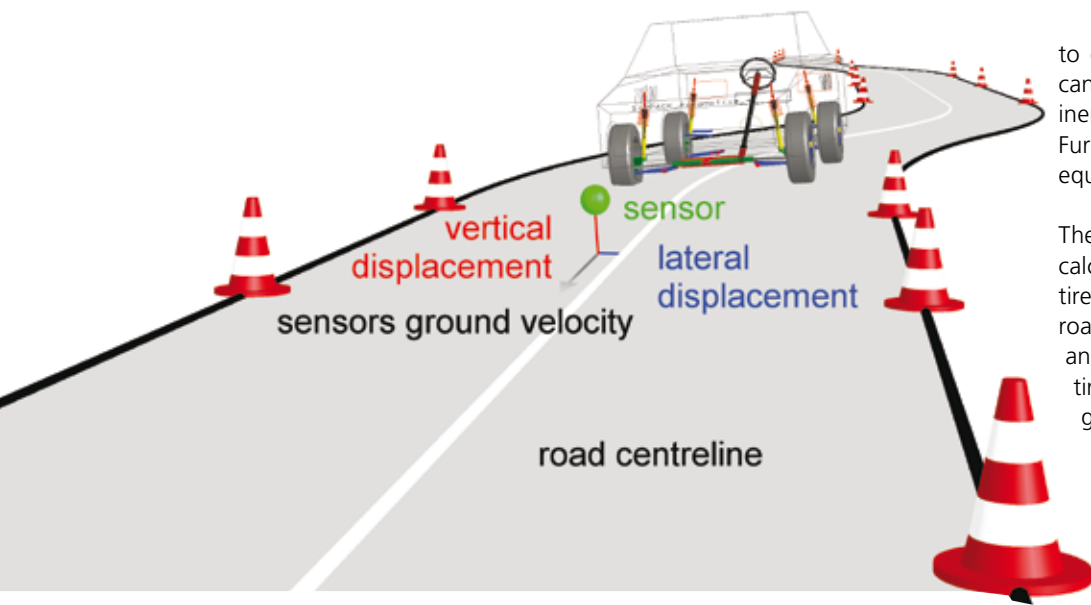


Fig. 5: Vehicle road sensor

“best” contact point is suggested at all knot vectors elements. Second, the iteration process (formula 10) can be limited to local intervals to avoid discontinuity.

ADDITIONAL ROAD SENSOR DATA

Several use cases (e.g., a driver model) requires the online measurement of the vehicle to road interaction. This measurement is performed by a second user force element as shown in Fig. 5. By defining a sensormarker M , the following measurements are done:

- Vertical displacement to the road in M_z -axes
- Lateral distance to the road centerline
- Orientation difference between the measurement marker and centerline
- Derivatives with respect to time by calculation of the sensor’s ground velocity
- Surface coordinates u and v

These measurements allow realization of different driver models within pure SIMPACK simulation using the “control elements” interface or by a Simulink® co-simulation. By providing the surface coordinates, it is also possible to define a reference line by $v_{ref} = f(u)$, e.g., to perform lap time optimizations.

NURBS ROAD TOOLBOX

To enable user-friendly creation of NURBS road files and also to allow simulation result visualization, a MATLAB® toolbox has been developed. This toolbox includes a NURBS-class to execute the required functions. The toolbox is integrated into a graphical user interface but can also be used by the

MATLAB command window. The following features are implemented:

- Import functions:
 - OpenCRG [4]
 - IGES data [5]
 - BAST Georohdaten
 - MATLAB data
- Parameterized creation of standard road surfaces, for example:
 - Roller drum test rigs
 - Curvature segments with specified banking angle
 - Some circuit roads
 - Single/ double lane change maneuvers
 - Random z-excitation surface
- Visualization
- Export functions:
 - Wave front*.obj data for road visualization within SIMPACK
 - Binary*.nrb data which can be loaded by the user force elements
 - MATLAB data

The MATLAB toolbox enables the user to automate the development process over the following steps: creating the road data, setting up the inertial conditions, performing a parameter variation, starting a Simulink co-simulation, saving the data, and visualizing the simulation results. Sample simulation results from a double lane change maneuver are shown in Fig. 6.

SIMULATION ENVIRONMENT

Compared to the original SIMPACK tire road model, the new user element does not need a track joint

to couple the vehicle. The vehicle’s chassis can be connected to any other body or the inertia frame with a joint of any freedom. Furthermore, the road body need not be equal to the inertia frame.

The user tire road force element is used to calculate the tire forces between road and tire body. The force element requires the road reference marker as the “from marker”, and the tire marker as the “to marker”. A tire data file is required to define the tire’s geometry, tire force calculation type and the tire’s physical properties. If no road file is selected, the x - y -plane ($z=0$) is used as the road surface.

Additionally, it is possible to specify a time dependent modification of road excitation or friction coefficient.

APPLICATION

The new tire road model is used at the IVK/ FKFS for different applications:

Validation of Torque Vector Control Systems and Driver Modeling:

To evaluate embedded systems, it is necessary to perform closed loop maneuvers, e.g., double lane change, skid pad driving, or variation of friction coefficient and banking angle while driving different curvature segments. These driving maneuvers are

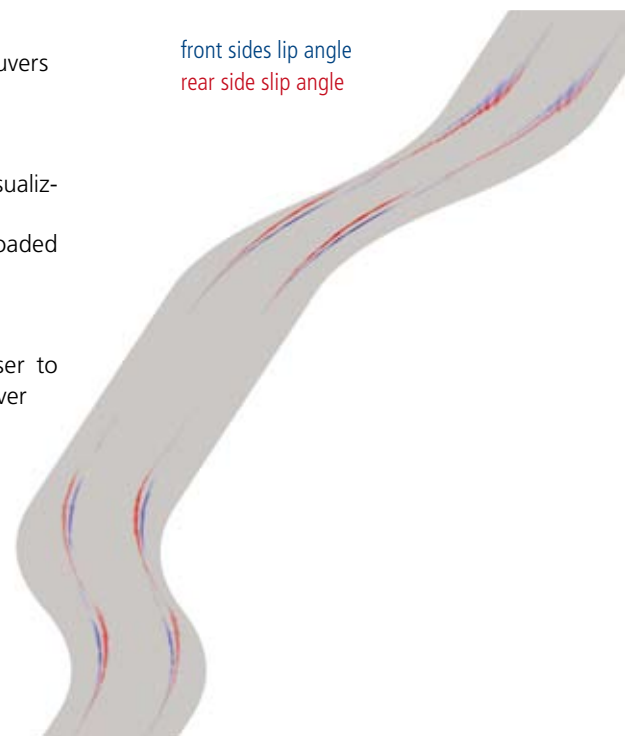


Fig. 6: Data visualisation of a double lane change maneuver

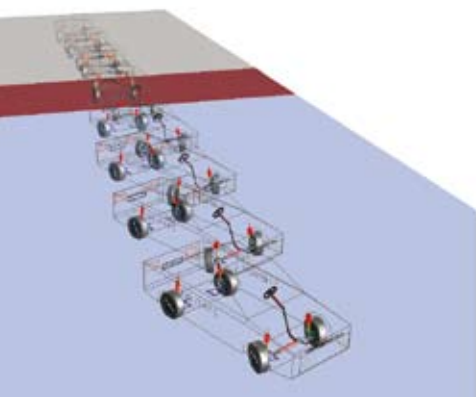
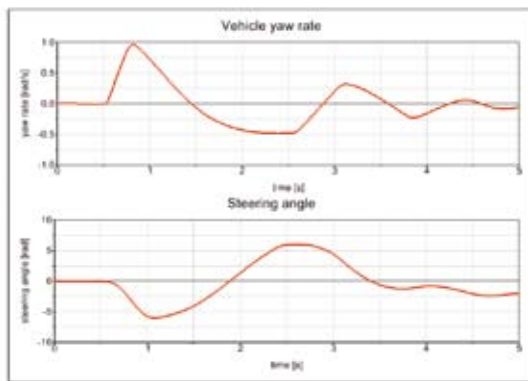


Fig. 7: Skid pad



predestined for automated simulation with parameter variation. The performance of most driving maneuvers running a Simulink co-simulated driver model is real time capable with a sampling period of 0.001 seconds.

Performing Test Rig Simulations:

The development of vehicle dynamic test benches requires detailed information about body stresses, dominating forces, measurement errors or real time capability. Many of these requirements can be estimated by performing test rig simulations within the SIMPACK environment. These simulations require relative calculation of the tire's state with moveable road bodies and an own road reference system for each tire. The test rig excitation can be determined by pre-processing a specific maneuver or by online calculation of the dynamic system.

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Simulating Real Road Measurement Data:

To simulate real road measurement data for any kind of driving dynamic applications, several methods are implemented in the MATLAB toolbox to create NURBS roads from different data types. The user can specify longitudinal and lateral interpolation order and perform automated interpolation point optimization and reduction. Wave front*.obj files can also be created for visualization in SIMPACK. Simulating NURBS roads generated from measurement data is the same process (with the same performance) as simulation with user defined road surfaces.

Vehicle energy demand assessments:

Several user cases, e.g., energy demand calculation, require a more detailed rolling resistance model implemented in the tire force element. Compared to vehicle dynamic application, cumulative energy balance is of greater importance. Some simplifications

in existing handling tire models must be corrected by means of precise force application, point calculation and extended rolling resistance force modeling. To evaluate tire force element modifications, some tire test benches have been created. These test benches allow easy modification of road's banking angle, curvature diameter and driving velocity.

A selection of the mentioned application samples are shown in Figs. 7–9.

The introduced universal tire road model environment enables the simulation of any kind of advanced driving dynamic application.

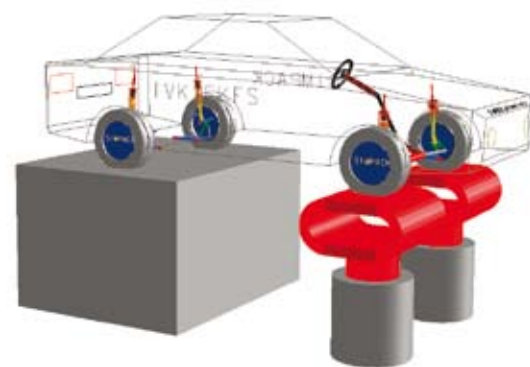


Fig. 9: Test bench

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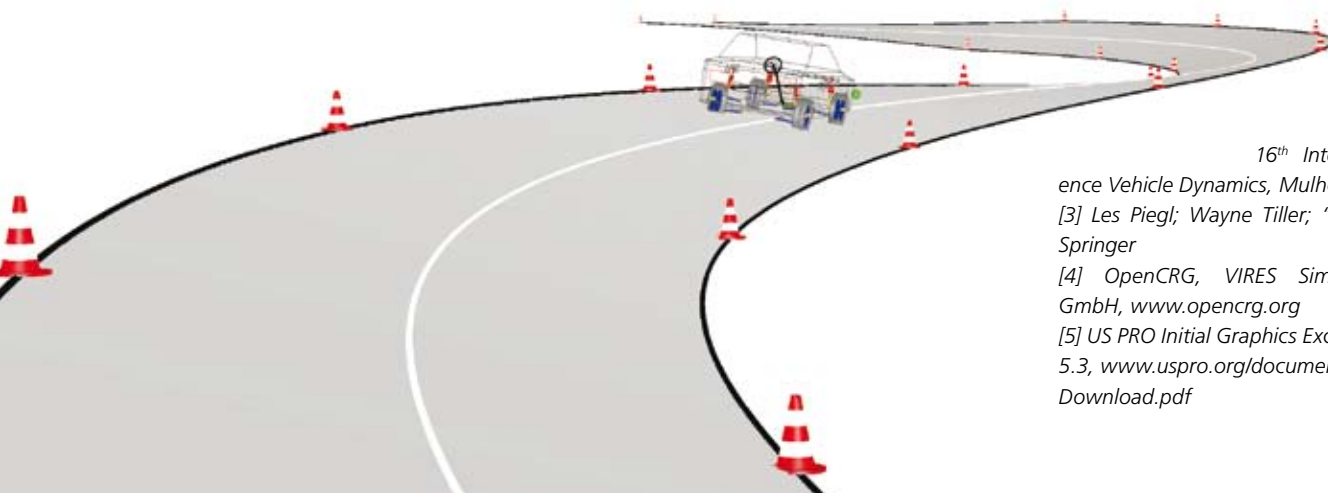


Fig. 8: Banked curves