

BikeSim[®] 2: Math Models

BikeSim 2.0 provides highly efficient custom computer programs optimized for solving equations in math models that represent the dynamic behavior of vehicles. The built-in VehicleSim[®] command language can be used to add new capabilities at run time to customize and extend the math models. Further, the models can communicate with other software (Simulink, LabView, ETAS ASCET, Custom C/C++ programs, Visual Basic, etc.).

Vehicle Math Models

Nonlinear Properties and Tables

- Nonlinear properties are typically specified with VehicleSim tables. These can be set to use constants, linear coefficients, nonlinear tables with linear or spline interpolation, and in some cases, 2D interpolation. (Up to 11 calculation options are available.)
- When simpler methods are selected (coefficients or linear interpolation), the simulations can run even faster.
- There are no built-in limits to the lengths of tables.

Control Inputs

- All control inputs can be specified using built-in model options. They can also be defined by equations at runtime using VehicleSim commands. Or, they can be imported from other software such as Simulink, LabView, or custom programs written in C, VB, etc.
- Built-in steering control can be specified with open-loop steering torque or closed-loop lean angle control. Alternatively, a built-in rider model can be selected; it follows a path relative to the road centerline, using rider lean and steer.
- Brake control is provided by several options, including lever/pedal forces and master cylinder pressure. Alternatively, a speed-controller can control throttle and brakes using a target speed relative to either time or position along the road.
- Throttle control is specified as an open-loop function of time. Alternatively, throttle can be handled by the speed-controller.
- Gear shifting and clutch controls are specified as open-loop functions of time. Alternatively, automatic (closed loop) shifting and clutch control can be used.

- Rider body control is provided including upper body lean, lateral and vertical hip movement as an open-loop function of time or position along the road.

Wind and Aerodynamic Effects

- Three aerodynamic forces and moments are applied to the sprung mass (drag, lift, and pitch).

3D Road Geometry and Friction

- Horizontal geometry of a road design path (typically the centerline) is defined by a sequence of X-Y coordinates. They are fitted by a spline to define a continuously curved horizontal path. They are also used to define station (distance along the path).
- Vertical geometry of the design path is defined by a sequence of elevation values as a function of station. The elevation values are interpolated by a method specified at run time.
- Off-center elevation relative to the design path is specified with a 2D table, based on station and lateral distance from the design path. Two tables are used to help separate design geometry (superelevation, ditches, road camber, etc.) from special events (bumps, potholes, etc.) or roughness data.
- Road profiles are also included that follow the vehicle to enable the use of high-frequency measured roughness data without requiring a fully detailed 3D map.
- Friction is specified relative to the design path with a 2D table based on station and lateral distance from the path.
- As an alternative to the road concept, a 3D ground surface can be specified as a table of Z values for a grid of global X and Y values.
- Road geometry can be imported from other software or defined by equations that are added at runtime.
- The VehicleSim API includes functions to provide access to the 3D road geometry for user-supplied equations for model extensions or additional outputs.

Suspensions

- The suspension models have full nonlinear kinematical behavior.
- Front suspension has compliance in longitudinal (bend) and roll (twist) relative to the main frame.

- The front suspension can be many types: *telescopic fork*, *McPherson strut*, *double wishbone*, *springer*, *bottom link*, etc. The detailed kinematic motion is able to represent *anti-dive* geometry.
- Rear suspensions can be a swing arm with or without parallel link. The model specifies detailed kinematic motion of wheel hub to represent *anti-jacking* geometry.
- Each wheel moves vertically. Longitudinal movement and dive angle of wheel hub are related to vertical position by nonlinear tables.
- Suspension springs are nonlinear and include hysteresis due to friction.
- Damper forces are nonlinear functions of stroke rate.
- Both spring and damper involve nonlinear kinematic lever ratio, which can represent many kinds of cushion mechanisms.
- A virtual kinematics and compliance (K&C) tester, that measures the kinematics and compliance of a simulated suspension model is included. This tool is useful for parameter study and validation.

Steering System

- The interactions between the suspension, steering, tire, and ground are handled with a detailed multibody model with steering axis.
- The steering system geometry is parameterized by caster angle, wheel axle height, fork length, and fork offset.
- The steering system includes mechanical limits and damping.
- Caster angle can be fixed relative to the main frame or variable with suspension stroke.

Brake System

- Master cylinder pressure is calculated by the control force input through the booster mechanism.
- The master cylinder pressure is proportioned for the actuator through a first-order transient lag.
- Brake torque is calculated by actuator pressure and disc mechanism.
- The brake system can involve external programs (e.g. Simulink) to provide advance control such as ABS, TCS, and stability control.
- The condition of wheel lockup is handled with a torsional spring-damper system to obtain the correct reaction torque when the wheel is locked.

Tires

- BikeSim includes several tire models, along with a program interface that supports external tire models.
- The original model uses the *Magic Formula* to represent longitudinal force, lateral force, and aligning moment as functions of slip, load, and camber. The shear forces are applied at a single contact point which moves around the tire circumference and laterally around the side wall: that automatically occurs overturning moment.
- An alternate model uses nonlinear tables to represent lateral force, longitudinal force, and aligning moment as functions of slip, load, and camber.
- Overturning moment due to the tire contact kinematical effect can be replaced with non-linear tables as functions of slip, load, and camber.
- Lateral and longitudinal forces and moments are combined using combined slip theory as published by Pacejka and Sharp (for table look up model).
- Variable friction conditions are handled using similarity, to maintain both linear and limit properties of the tire (for table look up model).
- Dynamics due to rolling are included using relaxation length for lateral and longitudinal slip.
- Special equations are used to maintain realistic tire behavior at low speeds, when the assumptions of a rolling tire are not valid.
- Rolling resistance is included.
- The complete TNO Delft-Tyre model is also included as an alternate model.
- External tire models can apply forces at either the ground contact point or the wheel center.
- Different models can be applied to different wheels.
- A virtual tire tester is included. It measures the shear forces and moments with respect to the kinematic values of the simulated tire. This tool is useful to visualize the characteristics of the tire model, especially Magic Formula versions.

Powertrain

- BikeSim has detailed powertrain models for chain drive and shaft drive. There is also a minimal model used for speed control in which power is applied directly to the wheels.
- Engine torque is defined with a 2D table that relates torque to throttle input and crankshaft angular velocity.
- The engine feeds torque to the transmission either through a mechanical clutch or through a hydraulic torque converter with a primary gear.

- The transmission converts torque and speed based on the current gear selection, with spin inertias and efficiencies that depend on the gear selection.
- The torque from the transmission goes to either a sprocket of chain mechanism or a driveshaft.
- The chain has tensional stiffness and damping. The force vectors for driving and engine braking affect the swing arm motion.
- The driveshaft has torsional stiffness and damping.
- Fuel consumption is defined with a 2D table based on engine speed and throttle.

Virtual Sensors and Reference Points

- BikeSim includes virtual sensors that can be attached to the bodies (main frame: 10, steer system: 4, front unsprung mass: 4, and rear unsprung mass: 4). Available outputs are: speed, acceleration, and angular rate on three axis directions.
- BikeSim includes reference points that can be located on the bodies (same numbers as sensors, but different locations). Each reference point outputs its global position. Also, three forces can be applied to each reference point, and three moments can be applied to each body from external programs or commands.

Solver Program Input and Outputs

The BikeSim solver programs use VehicleSim library routines for processing input files, performing standard calculations, and generating output files.

Input Data Files

- The solver programs read all inputs from text files. (These text files are normally generated automatically by BikeSim; users typically do not view them.) The files can be controlled from within BikeSim or externally.
- Input files for BikeSim math models follow a simple keyword-based format called the Parsfile. A typical BikeSim solver program can recognize thousands of keywords when processing input files.
- Parsfiles are efficient for software to read and write, while also being easy for people to read and edit.
- Parsfiles support the INCLUDE capability, allowing many advanced applications such as design of experiment (DOE), sensitivity, and customized automation methods.
- Values can be assigned directly to model parameters with numbers. Users can also specify values with numerical expressions (e.g., 1/16) or symbolic algebraic expressions involving other model variables.

- The solver programs process VehicleSim commands at run time that define new variables, add equations to the model, change units for variables, and otherwise extend the original BikeSim model to meet custom requirements.
- The animator, plotter, and graphical user interface also use Parsfiles to store data.

Output Variables

- The solver programs generate over 800 output variables.
- Any subset of the list of variables can be specified at run time, to control the size and organization of output files.
- New output variables can be defined at runtime.
- BikeSim provides a graphical interface for browsing the lists of available variables, sorting by several categories.
- All variables are described in documentation files in both text and spreadsheet format.
- Output variables are used for several purposes:
 - Make plots that show vehicle behavior.
 - Input to post-processing software.
 - Motion information for the animator.
 - Possible inputs for external model extensions.
 - Define conditions for “events” when new vehicle or control properties take effect.

Working with Simulink® and External Models

- On Windows machines, the BikeSim math models are DLL files that run in many environments:
 - The BikeSim graphical database runs the math models with no additional software.
 - The math models run as blocks in MATLAB/Simulink, LabView, and other simulation environments.
 - The math models work with Visual Basic, MATLAB, and other programming languages that can load DLL files and access their functions.
 - The math models run under the control of Windows commands.
- Multiple instances of a math model can run simultaneously in Simulink and other environments to simulate multiple vehicles that interact dynamically.
- C/C++ can be used to extend the math models, accessing thousands of parameters and variables using the VehicleSim API.

- Math model solver programs are compiled to native code for real-time systems to interface with the RT test control software.

Input Variables

- Calculations from external models and measurements from hardware in the loop can be imported into BikeSim. These include most forces and moments, fluid pressures, control variables, ground geometry under each tire, etc.
- The vehicle models can import nearly 200 variables.
- Most of the import variables can be combined with native internal variables. Users can specify one of three possible actions for each activated import variable:
 1. replace the native variable,
 2. add to the native variable, or
 3. multiply with the native variable.
- BikeSim provides a browser for activating import variables from the lists of all those that are available.
- New import variables can be defined at run time to pass through data from other software. E.g., variables from Simulink can be passed through to the animator.

Export Variables

- All variables available for writing to output files are also available for export to Simulink or external code.
- Variables are exported only if activated at run time. Most Simulink models receive only a small number of the potential export variables from BikeSim, simplifying the integration with other software.
- BikeSim provides a browser for activating export variables from the lists of all those that are available.
- New export variables can be defined at run time.

Multibody Model Specifications

State Variables and Degrees of Freedom

- The sprung mass of the motorcycle is a rigid body with six degrees of freedom (DOF).
- Steering system has two compliance DOF (bend and twist) and one steering DOF.
- Each suspension has an independent multibody DOF—the vertical movement of the wheel center.
- Other suspension motions, such as dive and longitudinal position of wheel are constrained as nonlinear functions of the vertical movement.
- Each wheel has one spin DOF.

- Rider body has two DOF — upper body lean and hip lateral translation relative to the motorcycle main frame.
- Other rider body motions, such as vertical translation of rider hip, lateral and vertical translation of rider lower body C.G. are constrained as nonlinear functions of the lateral movement of the hip.
- The brake fluid in each actuator has one DOF.
- Each tire has two dynamic DOF: one for lagged lateral slip, the other for lagged longitudinal slip.
- The TNO Delft Tyre model has additional DOF.
- The engine crankshaft has one DOF, and the engine torque has a dynamic lag in response to throttle change.
- The gear box sprocket (or driveshaft) has one rotational DOF.
- Fuel consumption has one DOF.
- Every suspension spring has a friction DOF.
- Each wheel has one DOF for locked-wheel dynamics.

Equation Form

- The equations of motion are derived from first principals for full nonlinear 3D motions of multiple connected rigid bodies.
- The equations of motion are ordinary differential equations (ODE's) that are “non-stiff” and can be solved with most numerical integration methods.
- The built-in VehicleSim library provides five methods for solving the ODE's. These include three second-order methods (Adams-Bashforth, Adams-Moulton, and Runge-Kutta), plus third-order and fourth-order Adams-Moulton methods.
- All methods run at a fixed time step and work well for real-time applications with hardware in the loop (HIL).
- The algorithms work well with measured and sampled data sources (tables), eliminating the need for spline interpolation for many tables used in the models. (However, spline interpolation is supported to provide a full range of run-time options.)
- The native equations are compiled with extensive optimizations and are embedded in the solver programs where they maintain their high efficiency regardless of what other software that might be running concurrently (e.g., Simulink).