truckSIM®: Math Models

TruckSim provides custom computer programs optimized for solving equations in math models that represent the dynamic behavior of vehicles. The VehicleSim® (VS) architecture includes the built-in VS command scripting language to add new capabilities at run time to automate tests or add features to the math models. Further, the models can work with other software (Simulink, LabVIEW, ETAS ASCET, Custom C/C++ programs, Visual Basic, etc.) for automation or extensions to the math models.

Vehicle Math Models

Configurable Table Functions

- Potentially nonlinear relationships between independent and dependent variables are defined with VS configurable functions that are set at runtime to use one of many calculation options:
  - Constants.
  - Linear coefficients.
  - Nonlinear tables with several interpolation methods involving one or two independent variables.
  - Algebraic formulas involving other variables.
- When simpler methods are selected (coefficients or linear interpolation), the simulations can run even faster.
- There is no built-in limit to the length of tables.
- The independent and dependent variables can be transformed in support of normalized functions.

Driver Controls

- All driver controls can be specified using built-in model options, or defined by equations added at runtime with VS commands, or imported from other software.
- A built-in driver model can steer to follow a target path.
- The driver model can control speed based on target speed and acceleration limits, curvature of the target path, and 3D road geometry (banking, grade, curvature).
- The target path for the driver model can be relative to the road reference line or independent of the road line.
- Gear shifting and clutch controls can be handled with shift schedules and automatic throttle-clutch interactions.
- Closed-loop and open-loop controls can be combined to simulate intervention systems.

Wind and Aerodynamic Effects

- Aerodynamic forces and moments are applied to the sprung masses (lead unit and load-carrying trailers).
- These forces and moments are configurable functions of aerodynamic slip.
- Ambient wind speed and heading can be set with tables, runtime equations, or imported from other software.

3D Road Geometry and Friction

- Horizontal geometry of a road reference line is defined by X-Y coordinates that are fitted by spline interpolation to define a continuously curved path.
- Vertical elevation of the reference line is defined as a configurable function of station, where station is the distance along the reference line.
- Off-center elevation is specified with a configurable function of station and lateral distance.
- The road can have variable width, allowing highly efficient descriptions of complex geometries such as lane merging, ruts and ditches that "wander," variable-width banked turns, etc.
- Road profiles are included that "wander" to follow the vehicle wherever it goes. This provides efficient use of high-frequency measured road roughness data.
- Friction is specified relative to the reference line with a variable-width function of station and lateral distance.
- Road geometry can be imported from other software or defined by equations that are added at runtime.
- The VS API includes functions to provide access to the 3D road geometry for user-supplied equations for model extensions or additional outputs.
- An alternative to the road concept is a 3D ground surface specified with a grid of X, Y and Z values.

Suspensions

- The suspension models have full nonlinear kinematical behavior and are asymmetric.
- TruckSim includes independent and solid axle suspensions.
- Every suspension has compliance in the lateral and longitudinal directions, and every wheel has toe and camber compliance effects.
- All compliances can be represented with linear coefficients or nonlinear configurable functions.
- Suspension springs are nonlinear and include hysteresis due to friction.
- Separate forces are included for bump stops.
- Suspension roll moments include a nonlinear auxiliary roll moment.
- Dampers are nonlinear.
- Tandem and tridem suspensions include static load distributions, dynamic load transfer, and load transfer due to brake torque.

- TruckSim obtains roll and jacking forces as the natural results of full 3D kinematical curves and compliance effects for independent and solid-axle suspensions.

Frame Twist and Suspended Cabs

- Each vehicle math model is available with either rigid sprung masses or frame with twisting compliance that connect the bodies to the suspensions and engine.
- The models with frame twist also include suspended cabs in the lead unit.

Steering System

- The steer of each wheel from the steering system is added to the steer due to suspension kinematics and compliance effects.
- The steer due to the steering system is obtained from nonlinear tables that can be measured or obtained with simulated K&C tests.
- The steering model includes compliances in the steering column and tie rod. The steer is also modified by axle wrap, roll, and jounce.
- Steer torque at the steering wheel is obtained by calculating the total steering moment about the kingpins for the front wheels.
- Special equations are used for low-speed conditions to simulate ground friction steer torque.

Brake System

- The control input pressure from the master cylinder is proportioned for each actuator as a nonlinear function of pressure and wheel dynamic load.
- Hydraulic/air dynamics are modeled with a first-order transient lag, plus a pure time delay for open-loop pressure controls.
- Brake torque is a nonlinear function of pressure.
- A simple ABS controller is included.
- Special equations handle wheel lockup to obtain the correct reaction torque and avoid numerical instability.

Tires

- TruckSim includes several tire models. It is ready to run with a table-based basic model, an extended model (more tables for camber effects), the Pacejka 5.2 version of the Magic Formula, and MF-Tyre from TNO.
- TruckSim is also ready to run with MF-Swift from TNO and FTire from COSIN (extra licenses are required from TNO and COSIN, respectively, to use their models).
- Dual tires are available for all wheels.
- The built-in models use nonlinear tables to represent lateral force, longitudinal force, aligning moment, and overturning moment as functions of slip, load, and camber.
- Lateral and longitudinal forces and moments are combined in the built-in models using combined slip theory as published by Pacejka and Sharp.
- Variable friction conditions are handled using similarity to maintain both linear and limit properties of the tire. Separate coefficients are used for X and Y components.
- Dynamics due to rolling are included using relaxation length for lateral and longitudinal slip. Relaxation lengths can be modified dynamically during the run.
- Special equations are used to maintain realistic tire behavior at low speeds when the assumptions of a rolling tire are not valid.
- External tire models can apply forces at either the ground contact point or the wheel center.
- Different models can be applied to different wheels of the same vehicle.

Powertrain

- TruckSim has detailed powertrain models for variable drive settings (4x2, 4x4, 6x2, 6x4, 6x6, etc.) with up to five drive axles on the lead unit. Alternatively, a simple speed control is available in which torque is applied directly to the wheels on the lead unit.
- Engine torque is defined with a 2D table that relates torque to throttle input and crankshaft angular velocity.
- Fuel consumption is defined with a 2D table.
- The engine feeds torque to the transmission either through a hydraulic torque converter or through a mechanical clutch.
- 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 a differential for a single-axle drive system. With two-axle drive systems, the transmission applies torque to a transfer case with a torque bias. Additional transfer cases are added for drive systems with up to five axles.
- The transfer case unit and differential models are similar. All have four model options:
    1. Always locked. In this case the locking is modeled with a torsional spring and damper.
    2. Viscous coupling. In this case the torque differential is defined with a table based on the speed difference.
    3. Coupling is applied using a clutch. The differential clutch has built-in control logic (i.e. LSD: limited slip differential) that can be used, or it can be controlled externally. This can be with or without viscous coupling.

4. Yaw control differential system, which involves two clutches with reduction gears in parallel over a differential. The system allows control of the torque distribution between left and right, or front and rear. This can be with or without viscous coupling.

- Each transfer case has a torque bias that can be used with any of the above non-locked options.
- Twin-clutch is an alternative to an axle differential. The system involves a gearbox in the middle of the axle and two clutches between each wheel and the gearbox.
- Torsional compliance of the driveline is characterized by a natural frequency and damping ratio.

Sensors and Traffic

- The models include several kinds of virtual sensors that detect various types of vehicle motion, including acceleration, speed, and previews of vehicle position on the road ahead.
- The models include reference points and associated forces and moments that are defined at runtime to extend the model.
- Up to 99 moving objects can be added that are updated automatically to convert simple road-based commands into full 3D geometry. The objects can be recycled for extensive runs so they reappear after they go out of view.
- Motion of an object can be constant, set with algebraic equations, set with differential equations, or imported from third-party software.
- Up to 20 range and detection sensors are available to detect the moving objects. (An extra license is required.)
- Each detection includes 11 variables that can be exported to external controllers (e.g., ADAS).
- Objects can block each other (occlusion). The sensor detection variables respond only to the portion of the object that is within the field of view.

Solver Program Input and Outputs

The TruckSim solver programs use VS 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 TruckSim; users typically do not view them.) The files can be controlled from within TruckSim or externally.
- Input files for TruckSim math models follow a simple keyword-based format called the Parsfile. A typical TruckSim solver program can recognize thousands of keywords when processing input Parsfiles.
- 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 experiments (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 VS commands at run time that define new variables, add equations to the model, change units for variables, and otherwise extend the original TruckSim model to meet custom requirements.
- The animator, plotter, and graphical user interface also use Parsfiles to store and transfer information.

Output Variables

- The solver programs generate from 800 to thousands of output variables, depending on the type of vehicle, number of moving objects, and number of sensors.
- Any subset of the list of variables can be specified at run time to control the size and organization of output files.
- Writing to file can be enabled and disabled during the run to save only interesting results from long simulations.
- New output variables can be defined at runtime.
- TruckSim 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.
    - Motion information for the animator.
    - Define conditions for “events” when new vehicle or control properties take effect.
    - Used in formulas added at runtime to define other variables.
    - Export to other software during the simulation.
    - Input to post-processing software.

Working with Simulink® and External Models

- On Windows machines, the TruckSim math models are DLL files that run in many environments:
    - TruckSim runs the models with no additional software.
    - They run as blocks in MATLAB/Simulink, LabVIEW, and other simulation environments.
    - They work with Visual Basic, MATLAB, and other programming languages that can load DLL files and access their functions with the VS API.
    - They run under the control of Windows commands.

- TruckSim includes both 32-bit and 64-bit DLLs.

- Multiple instances of a math model can run simultaneously to simulate multiple vehicles in Simulink, LabVIEW, and other environments.
- C/C++ can be used to extend the math models, accessing thousands of parameters and variables using the VS API.
- MATLAB, Visual Basic (VB), and other languages can run the models for automation and extend the models using import and export variables.
- Math model solver programs are compiled to native code for real-time systems to interface with the RT test control software.

Input Variables

- Values from external models or hardware-in-the-loop can be imported into TruckSim. These include most forces and moments, fluid pressures, controls, ground geometry under each tire, etc.
- The vehicle models without trailers or sensors can import at least 375 built-in variables. Those with trailers can import many more.
- Most of the import variables can be combined with native internal variables with one of three modes:
  1. replace the native variable
  2. add to the native variable
  3. multiply with the native variable
- TruckSim 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 as needed to be compatible with the external model.
- New export variables can be defined at run time.
- TruckSim provides a browser for activating export variables from the lists of all those that are available.

Multibody Model Specifications

State Variables and Degrees of Freedom

The math models have ordinary differential equations for the dynamics of multibody system including rigid bodies, fluids, tires, controllers, and other dynamic components.

- The sprung mass of the motor vehicle is a rigid body with six degrees of freedom (DOF).
- Each wheel has one spin DOF.
- Each independent suspension has two multibody DOF: the vertical movements of the wheel centers.
- Each solid-axle suspension has two independent multibody DOF: the axle bounce and roll.
- Other suspension motions such as pitch, camber, lateral position, etc., are constrained as nonlinear functions of the independent variables.
- Each suspension has six compliance DOF.
- 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 engine crankshaft has one DOF and the engine torque has a dynamic lag in response to throttle change.
- Fuel consumption has one DOF.
- Every suspension spring and tire has a friction DOF, as does the steering system.
- Each wheel has a low-speed (parking lot) steering friction DOF.
- Power steering boost has a DOF.
- The ABS system has one DOF per brake actuator.

Equation Form

- The equations of motion in the TruckSim math models are derived (by machine via VS Lisp) 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 well behaved (not stiff).
- The built-in VS library provides five methods for solving the ODE's (Adams-Bashforth, Adams-Moulton, and Runge-Kutta methods).
- All methods run at a fixed time step and work well for real-time applications.
- The algorithms work well with measured and sampled data sources, even when there are discontinuities.
- The equations are compiled with extensive optimizations for efficient use either alone or with other software (e.g., Simulink, LabVIEW).

Initialization and Restarts

- TruckSim supports many initialization options, from automatic to detailed specification of any state variable.
- The complete state of the vehicle model is saved at the end of each run to support continuation later for advanced automation and optimization methods.
- The state of the model can be saved during a run and fully restored during the run, in support of advanced optimization methods and repetitive test sequences.