truck**SIM**®: **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:
  - o Constants.
  - o Linear coefficients.
  - o Nonlinear tables with several interpolation methods involving one or two independent variables.
  - o Algebraic formulas involving other variables.
- When simpler methods are selected (coefficients or linear interpolation), the simulations can run even faster.
- No built-in limit to the length of tables.
- The independent and dependent variables can be transformed in support of normalized functions.

VS Reference Paths

- Multiple VS Reference Paths can be defined, each with a sequence of segments (straight, arc, or XY table).
- Reference paths are used for driver controls, traffic vehicles, and road definitions.

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.
- The built-in driver model can steer to follow a target path, which can be changed during the run.
- 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).
- 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

- Six aerodynamic forces and moments are applied to the sprung mass of the lead unit and trailer(s).

- These forces and moments are Configurable Functions of aerodynamic slip, pitch, and ride height.
- Ambient wind speed and heading can be set with tables, runtime equations, or imported from other software.

3D Road Geometry and Friction

- Multiple roads are supported, each with its own reference path.
- Vertical elevation is added with several components, each specified as a function of path S (station) and L (lateral offset) coordinates.
- Roads can have variable width, allowing highly efficient descriptions of complex geometries.
- 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 path 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.

Suspensions

- TruckSim suspension models have full nonlinear kinematical behavior and are asymmetric.
- 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 either linear coefficients or nonlinear Configurable Functions.
- TruckSim supports independent and solid axle suspensions.
- Suspension springs and dampers are nonlinear and include hysteresis due to friction.
- Separate forces are included for bump stops.
- Mechanical ratios for the compression of springs, dampers, jounce and rebound stops are specified with Configurable Functions that can be nonlinear.
- Suspension roll moments include a nonlinear auxiliary roll moment and roll damper.
- 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.

Mechanical Simulation

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Frame Twist and Suspended Cabs

- Each vehicle math model is available with either rigid sprung masses or frames with torsional compliance that connect the bodies to the suspensions.

- The models with frame twist also include suspended cabs for the lead unit.

Steering System

- All wheels on the lead unit can be actively steered.

- 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 kingpin axes 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 wheel brake cylinder 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.

- The brake system has several options for providing ABS control from external programs such as Simulink, or using a simple built-in controller.

- Special equations handle wheel lockup to obtain the correct reaction torque and avoid numerical instability.

Tires

- Dual tires are available for all wheels.

- TruckSim includes several tire models. It runs 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 runs with MF-Swift from TNO and FTire from COSIN (extra licenses are required from TNO and COSIN, respectively, to use their models).

- Different models can be applied to different wheels of the same vehicle.

- The built-in models use nonlinear tables for lateral force, longitudinal force, aligning moment, and overturning moment as functions of slip, load, and camber.

- Special equations are used to maintain realistic tire behavior at low speed, including parking on a grade.

- 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.

- Transient effects of rolling are included using relaxation length. Relaxation lengths can be constant or defined as nonlinear functions of vertical force and slip.

- Tire contact can be handled with one, two, or four points to account for contact patch dimensions.

Powertrain

- TruckSim has detailed powertrain models for various 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 Configurable Function of 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.

- Continuously variable transmissions (CVT) are supported.

- 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 between the two output shafts.
  3. Coupling 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.
  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.

- 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.
- TruckSim provides tight, low-level integration with the commercial powertrain simulation software Cruise from AVL. The GUI in TruckSim and AVL-Cruise supports automatic connections. An optional license is needed to use the Cruise interface.

Sensors and Traffic

- The models include several kinds of virtual sensors that detect various types of vehicle motion, including acceleration, speed, and previews of the road ahead.
- 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, to 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 can be included that detect the moving objects. An optional license is needed to use the sensor feature.
- 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

- TruckSim Solvers read all inputs from text files that are normally generated automatically by TruckSim. These files can also be made externally for advanced applications.
- Input files for TruckSim Solvers follow a simple keyword-based format called the Parsfile. TruckSim Solvers 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.
- Each input line can optionally specify alternate units for the specified input parameter.
- 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.
- TruckSim Solvers process VS Commands at runtime that define new variables, add equations to the model, change units for variables, and otherwise extend the original TruckSim model to meet custom requirements.
- Parsfiles support the INCLUDE capability, allowing many advanced applications such as design of experiments (DOE), sensitivity studies, and automation.
- The animator, plotter, and graphical user interface also use Parsfiles to store data.

Output Variables

- TruckSim Solvers generate from 600 to thousands of output variables, depending on the number of trailers, sensors, traffic vehicles, etc.
- Commands used at runtime add sets of motion outputs, driver preview points, and other outputs as needed.
- A subset of the available outputs can be specified at runtime, 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.
- New output variables can be defined at runtime.
- TruckSim provides a GUI for browsing the lists of available variables, sorting by several categories.
- All variables are described in documentation files in both text and spreadsheet format.
- Outputs can be written to 32- or 64-bit binary files.
- Output variables are used for several purposes:
  - o Make plots that show vehicle behavior.
  - o Input to post-processing software.
  - o Motion information for the video visualization.
  - o Used in formulas added at runtime to define other variables.
  - o Export to other software during the simulation.

Working with Simulink® and External Models

- On Windows machines, the TruckSim Math Models are DLL files that run in many environments:
  - o TruckSim runs models with no additional software.
  - o Models run as blocks in MATLAB/Simulink, LabVIEW, and other simulation environments.
  - o TruckSim S-Function supports multiple-port connections, with Import and Export variables activated with point and click browsing in the GUI.
  - o Models work with Visual Basic, MATLAB, and other programming languages that can load DLL files and access their functions with the VS API.
- 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 with Windows COM for automation.
- Math model solver programs are compiled to native code for real-time systems to interface with the RT test control software.
- TruckSim has a LINEARIZE command to generate linearized A, B, C, and D matrices for use in MATLAB.
- TruckSim solvers have built-in commands for adding forces and moments to extend the model.

Input Variables
- Calculations from external models and measurements from hardware in the loop (HIL) can be imported into TruckSim. These include most forces and moments, fluid pressures, controls, ground geometry under each tire, etc.
- The vehicle models can import values for hundreds of built-in variables.
- 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, or
  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 runtime 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 runtime, as needed to be compatible with the external model.
- New export variables can be defined at runtime.

Multibody Model Specifications

State Variables and Degrees of Freedom
TruckSim Math Models have ordinary differential equations for multibody system dynamics, fluids, tires, controllers, and other dynamic parts.

- The multibody mechanical system for the motor vehicle and each trailer vehicle has mechanical degrees of freedom (DOF) representing the following:
  o The sprung mass is a rigid body with six DOF.

- o Each suspension has two DOF. (The 3D motions follow constraint data from K&C tests.)
  o Each wheel has one spin DOF.
- The TruckSim Math Model for a two-axle truck has over 110 ordinary differential equations (ODEs); vehicles with more axles and/or trailers can have hundreds more. Each multibody DOF has two ODEs; other equations represent the dynamics of components:
  o Each tire has two DOFs for lagged response.
  o TNO Delft Tyre and COSIN FTire add more DOFs.
  o The fluid in each brake cylinder has one DOF.
  o The engine crankshaft has one DOF.
  o Throttle has a lag with one DOF.
  o Fuel consumption has one DOF.
- TruckSim Math Models have hundreds of state variables, needed to fully define the state of the system (along with parameters and Configurable Function definitions). These include the ODE variables plus others:
  o Each friction element has a state variable for hysteresis (suspension springs, steering system, low-speed tire steer).
  o Clutches and built-in controllers (e.g., ABS) have locked states.
  o Other dynamic mode conditions have state variables.

Equation Form
- The equations of motion are derived from first principals for 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 in support of 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.