TruckSim® 7: Math Models

TruckSim 7 uses efficient machine-generated solver programs optimized for specific sets of equations that represent the dynamic behavior of specific heavy truck vehicles. These solvers support built-in VehicleSim® command language that can be used to add new capabilities at run time. Further, the models can communicate with other software (Simulink, LabView, ETAS ASCET, Custom C/C++ programs) to work with other math models.

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 run even faster.
- There are no built-in limits to the lengths of tables.
- Most tables have associated gains and offsets that can be used in sensitivity or optimization studies.

Control Inputs

- All control inputs can be specified using built-in model options. Or, they can be defined with new equations at runtime using VehicleSim commands. Or, they can be imported from other software such as Simulink.
- Built-in steering control can be specified with open-loop steering wheel angle or a driver model that follows a path relative to a road centerline.
- Brake and throttle control are specified as open-loop functions of time, or, a speed-controller is used to control throttle and brakes to follow a target speed relative to either time or position along the road.
- Gear shifting and clutch controls are specified as open-loop functions of time, or, automatic shifting and clutch control are used.

3D Road Geometry and Friction

- Horizontal geometry of a road design path (e.g., 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 at corresponding values 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 2D tables, based on station and lateral distance from the design path. Two tables are used to keep separate datasets for design data and special events (bumps, potholes, etc.) and roughness data.
- Road profiles are 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 defined for a grid of X and Y values.
- Road geometry can be imported from other software or specified at runtime with VehicleSim commands.

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 nonlinear tabular functions of aerodynamic slip.
- Wind amplitude and heading can be specified as tabular functions of time, or with equations specified at run time, or by importing from other software.

Suspensions

- The suspension models have full nonlinear kinematical behavior and can be asymmetric.
- In a solid axle suspension, the main variables are vertical movement and roll of an axle rigid body. Forward movement, lateral movement, steer, and dive are defined by nonlinear tables.
- In an independent suspension, longitudinal and lateral movements of each wheel are constrained by nonlinear tables to follow 3D paths defined as functions of vertical movement. Camber, toe, and dive angles are also related to suspension deflection by nonlinear tables.
- Every suspension has compliance in the lateral and longitudinal directions.
- Every wheel has compliance that affects toe and camber in response to tire shear forces and moments.

- TruckSim obtains roll and jacking forces as the natural results of full 3D kinematical curves and compliance effects for independent and solid-axle suspension.
- Suspension springs are nonlinear and include hysteresis due to friction. The characteristics depend on the static load, to properly represent air spring behavior.
- Dampers are nonlinear.
- Suspension roll moments include a nonlinear auxiliary roll moment to account for roll stiffness/compliance beyond the effects of the springs.
- Tandem and tridem suspensions include static load distributions, dynamic load transfer, and load transfer due to brake torque.

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 by combining the steering wheel control with a nominal gear ratio and a nonlinear table relates geared-down steering wheel angle to road steer angle, with Ackerman and other effects.
- The steer is modified by compliances at 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.
- Wheel lockup is handled with a torsional spring-damper system to avoid numerical instabilities and to obtain the correct reaction torque during lockup.

Tires

- Dual tires are available for all wheels.
- TruckSim includes several tire models, along with a program interface that supports external tire models.
- The main tire model uses nonlinear tables to represent lateral force, longitudinal force, aligning moment, and overturning moment as functions of slip, load, and camber.
- A simpler model is included that neglects overturning moment and nonlinear camber effects.
- Lateral and longitudinal forces and moments are combined using combined slip theory.
- 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.
- Special equations are used to maintain realistic tire behavior at low speeds, when the assumptions of a rolling tire are not valid.
- The Pacejka 5.2 version of the Magic Formula is included as an alternative model option.
- 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 four drive axles. There is also a minimal model used for speed control in which power 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. There is also a dynamic lag due to throttle change.
- Fuel consumption is defined with a 2D table based on engine speed and throttle.
- The powertrain can include either a hydraulic torque converter or 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 single-axle drive systems. With more driven axles, the transmission applies torque to a transfer case with user-specified torque bias.
- The transfer case unit and differential models are similar. All have four model options:
  1. Always locked. In this case the locking is modeling 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 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.
- The center unit 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 gear box in the middle of the axle and two clutches between each wheel and the gearbox. The clutch positions are controlled externally.

Solver Program Input and Outputs

The TruckSim solver programs use VehicleSim library routines for processing input files, performing standard calculations, and generating output files, while maintaining the high speed for which TruckSim is known.

Input Data Files

- 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 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.
- TruckSim normally generates Parsfiles automatically; users typically do not view them. The files can be controlled by either by TruckSim or external software.
- 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 TruckSim model to meet custom requirements.
- The animator, plotter, and graphical user interface also use Parsfiles to store data.

Output Variables

- The solver programs generate between 750 and 2000 output variables, depending on the type of vehicle.
- 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 using VehicleSim commands.
- 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.
- Output variables are used for several purposes:
  - Make plots that show vehicle behavior.
  - Input to post-processing software.
  - Provide 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 TruckSim math models are DLL files that use the VehicleSim API and run in many environments:
  - The TruckSim graphical database runs the models with no additional software.
  - They run as blocks in MATLAB/Simulink, LabView, and other simulation environments.
  - They run under the control of Windows commands.
  - They work with external C via the VehicleSim API.

- 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.
- On real-time operating systems, solver programs are compiled to native programs that interface with the RT test control software.

Input Variables

- Values from external models or hardware in the loop can be imported into TruckSim. Optional inputs include most forces and moments, fluid pressures, control variables, ground geometry under each tire, etc.
- The vehicle models without trailers can import over 200 variables. Those with trailers can import over 350.
- Most of the import variables can be combined with native internal variables. At run time, users can specify one of three actions for each activated import variable:
    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 run time with VehicleSim commands to pass through information from other software such as Simulink.

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 they are activated at run time. Most Simulink models that use TruckSim receive only a small number of the potential variables that TruckSim can export, simplifying the integration with other software.
- TruckSim 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 using VehicleSim commands.

Multibody Model Specifications

State Variables and Degrees of Freedom

- 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 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- 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 most 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).