truckSIM®: Math Models

TruckSim math models simulate the dynamic behavior of vehicles, including combination vehicles with trailers. The VehicleSim® (VS) Math Model architecture is used.

TruckSim VS Math Models are built using dynamically linked VS Solver library files, available for 13 operating systems: Windows (32- and 64-bit), Linux, and real-time platforms used for hardware-in-the loop. The models work well with other software (Simulink, LabVIEW, FMI, ETAS ASCET, EPIC Unreal, Custom programs, etc.) for automation or extensions to the models.

A basic TruckSim model runs more than 10 times faster than real time on a typical Windows computer.

Multiple vehicles may be simulated simultaneously using a single VS Math Model, or by running multiple VS Math Models in parallel using external software such as Simulink.

Vehicle Math Models

Vehicle Configurations

- A vehicle has a lead unit with 0 to 31 semitrailers.
- A single-axle lead unit can be combined with a trailer to simulate an articulated vehicle.
- Each vehicle unit may have one or more suspensions, up to a limit of 128 suspensions in total for the vehicle.
- The suspensions may be organized in groups as needed to support tandem and tridem load sharing.
- Sprung masses may be simple rigid bodies or include frame rails that account for torsional compliance.
- The lead unit may have a suspended cab.
- Loader arms may be attached to any sprung mass.

Configurable Table Functions

- Potentially nonlinear relationships between variables are defined with VS Configurable Functions that can be:
    - Constants
    - Linear coefficients
    - Nonlinear tables with several interpolation methods involving one or two independent variables
    - User-defined formulas
- Configurable Functions include offset and gain transform parameters for dependent and independent variables.
- There is no built-in limit to the length of tables.

VS Reference Paths

- A VS path defines an S-L coordinate system (S = distance along path, L = lateral distance from path).
- Each path is a sequence of segments, where each segment may be straight, an arc, a clothoid, or an X-Y table.

- VS paths are used for driver controls, locating traffic vehicles, and defining 3D road properties.
- A VS Math Model supports up to 500 VS Paths.

Driver Controls

- Driver controls can be handled by built-in controllers, VS Command equations, or imports from external software.
- The closed-loop driver model (DM) can steer to follow a target path, which can be changed during the run.
- The DM controller handles forward and reverse speeds.
- Closed-loop Speed Controller (SC) for throttle and braking based on target speed or acceleration, or path.
- SC path preview uses 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 ADAS intervention systems.
- Steering wheel control can be by angle or torque.
- Open-loop braking can be pedal force or fluid pressure.

3D Road Geometry and Friction

- The 3D ground surface includes 3D geometry, friction, and a tire rolling resistance coefficient.
- The 3D surface may be a set of VS Roads or VS Terrain.
- Up to 200 VS Roads may be built with components:
    - VS Reference Path for S-L coordinate system.
    - Configurable Functions for elevation and friction using S-L coordinates and variable-width tables.
    - Boundaries to connect adjacent VS Roads.
- VS Terrain provides a single mesh-type ground surface, created with VS Scene Builder with several options:
    - Create interactively by dragging 3D Tiles.
    - Import datasets from OpenDRIVE format.
    - Import 3D FBX files from other software.
- Road profiles "wander" to follow the vehicle tires, providing high-frequency road roughness inputs. Road profiles are measured routinely by some road agencies.

Wind and Aerodynamic Effects

- Six aerodynamic forces and moments are applied to the sprung mass of each vehicle unit (lead units and trailers).
- These forces and moments are shaped by Configurable Functions of aerodynamic slip.
- Ambient wind speed and heading can be set with tables, runtime equations, or imported from other software.

Suspensions

- Suspensions can be generic/independent, solid axle, or independent with virtual steering axis.
  - o Wheel movement in a generic/independent suspension depends on jounce on both sides.
  - o Axle movement in a solid axle suspension depends on axle jounce and roll
  - o Wheel movement in a virtual steering axis suspension depends on jounce and steering rack travel.
- Independent and solid-axle suspensions can be either steered or non-steered.
- All suspensions have full nonlinear kinematical behavior and can be asymmetric.
- Suspension springs and dampers are nonlinear. The springs include hysteresis due to friction.
- All suspensions have lateral and longitudinal compliance; every wheel has toe and camber compliance.
- All compliances can be represented with linear coefficients or nonlinear configurable functions.
- Separate forces are included for jounce and rebound stops.
- Suspension roll moments include a nonlinear auxiliary roll moment and linear coefficient roll damper.

Steering System

- The interactions between the suspension, steering, tire, and ground are handled with a multibody model that uses an inclined kingpin axis, or 2D kinematics tables in the case of the virtual steering axis suspension.
- Use rack-and-pinion or recirculating ball.
- Steer angle of each road wheel is available as measured in a K&C rig or as rotation about the kingpin axis.
- Control the left wheel, the right wheel, or symmetric.
- The steering system includes detailed options for manual or dynamic power boost, including column assist.
- The steering system includes hysteresis, compliance, inertia, and damping.
- Special equations are used for low-speed conditions to simulate ground friction steer torque.
- Alternatively, steering can be provided by hydrostatic control of articulation or by skid steer.

Brake System

- Brake control can be set with pedal force (with or without boost) or master cylinder pressure.
- The control input pressure from the master cylinder is proportioned for each wheel-end brake actuator.
- Brake torque is modeled as a nonlinear function of actuator pressure and optional thermal effects.
- The brake system can use a built-in ABS controller or connect with external programs such as Simulink.

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

Tires

- TruckSim includes several installed tire models:
  - o A fully nonlinear and asymmetric table-based model
  - o An extended model (more tables for camber effects)
  - o A terramechanics-based (soft soil) model (64-bit Windows, single tires only)
  - o MF-Tyre from Siemens
- TruckSim supports external models (license required):
  - o MF-Swift from Siemens
  - o FTire from COSIN
  - o TameTire from Michelin
- User-defined tire models can connect with VS STI.
- External tire models can apply forces at either the ground contact point or the wheel center.
- Variable friction conditions are handled using similarity, to maintain both linear and limit properties of the tire.
- Transient effects of rolling are included using relaxation length. Relaxation lengths can be constant or defined as nonlinear functions of vertical force and slip.
- Special equations are used at low speeds.
- Tire contact can be handled with one to four points.
- Dual tires are available for all wheels.

Powertrain

- TruckSim has detailed powertrain models for various drive settings (4x2, 4x4, etc.) with up to five drive axles.
- The powertrain can drive axles for any vehicle unit or pair of consecutive units.
- The powertrain supports internal combustion (IC), electric motor + battery, and hybrid (IC + electric motor + battery + planetary gear).
- The hybrid and EV powertrain models support battery regeneration.
- Electrified axles are supported with either one or two motors per axle.
- IC engine torque is defined with a 2D Configurable Function based on RPM and throttle.
- The engine feeds torque to the transmission either through 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.
- Supports continuously variable transmissions (CVT).
- The transfer case unit and differential models are similar. All have four model options: (1) always locked, (2) viscous coupling, (3) coupling applied using a clutch

(controlled externally or with built-in logic), (4) yaw control differential system having two clutches. Torque distribution is controlled left and right, or front and rear.

- Each transfer case has a torque bias for non-locked options.
- Twin-clutch is an alternative to an axle differential.
- Torsional compliance of the driveline is included.
- Fuel consumption is defined with a 2D table.
- TruckSim supports external models from GT Suite.

Sensors and Traffic

- The models include several kinds of virtual sensors that detect various types of vehicle motion, including acceleration, speed, and jerk.
- Up to 200 moving objects can be added that are updated automatically to convert simple path-based commands into full 3D geometry.
- Motion of an object can be constant, set by specifying speed, controlled by acceleration (simple physics), set with algebraic equations, or imported via import variables.
- The objects can be recycled for extensive runs, to reappear after they go out of view.
- Objects that move based on speed or acceleration support off-tracking, for realistic low-speed traffic turns.
- Objects used to represent traffic vehicles support brake lights and reverse lights.
- Objects may be rectangular, circular, segment (e.g., signs), or polygonal.
- Segment objects have a limited viewing angle, to mimic signs and signals with limited visibility.
- Up to 99 ADAS range and detection sensors can be included that detect the moving objects. An optional license is needed for sensors (but not for objects).
- Each detection includes 24 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.
- Detection sensors can be placed on the vehicle or moving objects (to detect and simulate collisions).
- Objects may be attached to vehicle sprung masses to support ADAS simulations with multiple vehicles or provide details of collisions with pedestrians.

VS Math Model Input and Outputs

Input Data Files

- TruckSim reads all input from text files that are normally generated automatically by the Browser/GUI. These files can also be made externally for advanced applications.

- Input files for TruckSim follow a simple keyword-based format called the Parsfile. TruckSim can recognize thousands of keywords when processing input files.
- Each input line can optionally specify alternate units for a parameter.
- Values can be assigned directly to model parameters with numbers, numerical expressions (e.g., 1/16), or symbolic algebraic expressions involving other model variables.
- Parsfiles support the INCLUDE capability, allowing advanced applications such as design of experiments (DOE), sensitivity, and customized automation methods.

Output Variables

- TruckSim generates from 600 to thousands of built-in output variables, depending on whether there are trailers, sensors, traffic vehicles, etc.
- A subset of the available outputs 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.
- 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 files may be written in several binary forms (32-bit and 64-bit) or CSV (text) spreadsheet format.
- Output variables are used for several purposes:
  - Make plots that show vehicle behavior.
  - Motion information for video visualization.
  - Input to other post-processing software.
  - Export to other software during the simulation.

VS Commands and Python

VS Solvers include the VS Command scripting language for customizing the model and its operation. VS Commands are supported in all versions, including real-time systems.

- VS Commands can add new equations at several locations in the sequence of simulation calculations.
- VS Commands can add new parameters, output variables, and state variables as needed to extend the model.
- VS Commands can add new differential equations.
- VS Commands can add new functions to simplify other formulas or series of equations.
- VS Commands can define new units.
- VS Events monitor custom formulas to trigger the reading of a new Parsfile to change values, modes, etc. This is used to script complicated procedures.
- The Windows and Linux versions provide embedded Python in support of full programming options.

Working with Simulink® and External Software

- The TruckSim VS Math Model is made with functions from a dynamic library file.
    - The TruckSim GUI runs VS Math Models directly.
    - TruckSim includes MATLAB/Simulink S-Functions.
    - TruckSim works with LabVIEW.
    - TruckSim can generate functional mockup units (FMU) to run under the functional mockup interface (FMI).
- MATLAB, Visual Basic (VB), and other languages can operate the Browser/GUI using Windows COM.
- TruckSim has a `LINEARIZE` command to generate linearized A, B, C, and D matrices for use in MATLAB.
- The VS SDK (software development kit) is available for Windows and Linux. It includes numerous application program interfaces (APIs):
    - The VS Solver API is used to build and interact with VS Math Models from C/C++ and languages that can load a DLL file (Python, MATLAB, VB, etc.).
    - The STI API helps connect external tire models.
    - The Shared Camera Buffer API accesses 3D information from VS Visualizer cameras.
    - VS Output API helps read and write output VS files.
    - VS Table API supports Configurable Functions.
    - VS Terrain API works with VS Terrain files.
    - VS Connect enables co-simulation between EPIC Unreal and Simulink.

Import 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 with VS Commands 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 other external code.

- Variables are exported only if activated at runtime, as needed to be compatible with the external model.

Working with the EPIC Unreal Engine

- The VehicleSim Dynamics plugin for Unreal Engine includes the VS Solvers for TruckSim and TruckSim, allowing the vehicle models to operate within the Unreal environment.
- The VS Connect library is used to connect an Epic Unreal simulation with a simultaneous Simulink simulation, with both working with the TruckSim VS Solver.

Multibody Model Specifications

State Variables and Degrees of Freedom

TruckSim has ordinary differential equations (ODEs) for the dynamics of multibody systems, including rigid bodies, fluids, tires, controllers, and other dynamic parts. Additional state variables are used to define the state of the model for features such as friction, clutch slipping, controllers, etc.

- The number of ODEs and state variables depends on many options available in the model. The VS Solver is used to generate a list of all state variables for any given simulation setup.
- A basic 2-axle TruckSim model has 89 ODEs and a total of 296 state variables.

Equation Form

- The equations of motion are derived from first principles for 3D motions of multiple connected rigid bodies, using Kane's equations for the multibody dynamics and constraints.
- The equations of motion are ODEs that are not stiff.
- The built-in VS library provides six methods for solving the ODE's (Adams-Bashforth, Adams-Moulton, Runge-Kutta, and Euler methods).
- All methods run at a fixed time step and may be used for real-time HIL applications.
- The algorithms work well with measured and sampled data sources, even when there are discontinuities.
- The VS Solvers 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 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.