CarSIM: Math Models

CarSim 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:
  - 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.
- Open-loop steering can be angle or torque.
- Open-loop braking can be pedal force or master cylinder pressure.

Wind and Aerodynamic Effects

- Six aerodynamic forces and moments are applied to the sprung mass (both sprung masses if there is a trailer).
- 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

- Horizontal geometry of a road reference line is defined by X-Y coordinates that are fitted by spline 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.
- 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.
- The front and rear suspensions can be independent or solid axle; rear suspensions can also be twist axle.
- In a twist axle suspension, the wheels move together when there are no external forces, similar to a solid-axle suspension. Compliance effects are included to account for the twisting of a connecting beam.
- Suspension springs and dampers are nonlinear and include hysteresis due to friction.
- Separate forces are included for bump stops.

- Suspension roll moments include a nonlinear auxiliary roll moment.
- CarSim obtains roll and jacking forces as the natural results of full 3D kinematical curves and compliance effects for independent and solid-axle suspensions.

Steering System

- The interactions between the suspension, steering, tire, and ground are handled with a detailed multibody model that uses an inclined kingpin axis.
- The steering system includes specific details for rack-and-pinion and recirculating ball.
- Steer angle of each road wheel is available as rotation as measured in a K&C rig (in the sprung mass coordinate system), or as rotation about the kingpin axis.
- The steering system includes detailed options for manual or power boost (with a time constant).
- The steering system includes hysteresis, compliance, inertia, and damping.
- 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.
- Brake torque is modeled as a nonlinear function of actuator pressure.
- The brake system has several options for providing ABS control from external programs such as Simulink, or using a simple built-in controller.
- Thermal effects and hydraulic dynamics are included.
- Special equations handle wheel lockup to obtain the correct reaction torque and avoid numerical instability.

Tires

- CarSim 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.
- CarSim 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).
- 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

- CarSim has detailed powertrain models for front-wheel drive, rear-wheel drive, and four-wheel drive (all-wheel 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 configurable function of throttle input and crankshaft angular velocity.
- 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 front or rear-wheel drive systems. With four-wheel drive systems, the transmission applies torque to a center unit (e.g. transfer case) with a torque bias.
- The center 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 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.
- The center unit has a torque bias for 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.
- Fuel consumption is defined with a 2D configurable function of engine speed and throttle.

- Torsional compliance of the driveline can be characterized by a natural frequency and damping ratio.
- CarSim includes additional solver programs with extra multibody degrees of freedom (DOF) to include engine movements allowed by engine mount compliances. An optional license is needed to use the engine-mount models.
- CarSim provides tight, low-level integration with the commercial powertrain simulation software Cruise from AVL. The GUI in CarSim and AVL-Cruise supports automatic connections. An optional license is needed to use the automatic 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 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, to reappear after they go out of view.
- Up to 20 range and detection sensors can be included that detect the moving objects.
- Each detection includes 11 variables that can be exported to external controllers (e.g., ADAS).
- Motion of an object can be constant, set with algebraic equations, set with differential equations, or imported from third-party software.
- 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 CarSim 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 CarSim; users typically do not view them.) The files can be controlled from within CarSim or externally.
- Input files for CarSim math models follow a simple keyword-based format called the Parsfile. A typical CarSim 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 VS commands at run time that define new variables, add equations to the model, change units for variables, and otherwise extend the original CarSim model to meet custom requirements.
- The animator, plotter, and graphical user interface also use Parsfiles to store data.

Output Variables

- The solver programs generate from 750 to several thousand built-in output variables, depending on whether there is a trailer, sensors, sensor target, and traffic vehicles.
- 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.
- CarSim 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.
    - 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.

Working with Simulink® and External Models

- On Windows machines, the CarSim math models are DLL files that run in many environments:
    - CarSim 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.
    - CarSim 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

- Calculations from external models and measurements from hardware in the loop (HIL) can be imported into CarSim. These include most forces and moments, fluid pressures, controls, ground geometry under each tire, etc.
- The vehicle models without trailers or sensor can import at least 375 built-in variables. With trailers, there can be over 600.
- 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.
- CarSim 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.

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 parts.

- The multibody mechanical system for a four-wheeled vehicle has 15 mechanical degrees of freedom (DOF):
  - The sprung mass is a rigid body with six DOF.
  - Each suspension has two DOF. Other suspension motions, such as pitch, camber, lateral position, etc., are constrained by configurable functions.
  - Each wheel has one spin DOF.
  - The steering system has one DOF.
- The math model for a four-wheeled vehicle has over 110 ordinary differential equations (ODEs). Each multibody DOF has two equations; other equations represent the dynamics of components:
  - Each tire has two DOF for lagged response.
  - TNO Delft Tyre and COSIN Ftire add more DOF.
  - The brake fluid in each actuator has one DOF.
  - The temperature for each brake has one DOF.
  - The engine crankshaft has one DOF.
  - Throttle has a lag with one DOF.
  - Fuel consumption has one DOF.
  - Power steering and power brake each add one DOF.
- The engine mount models add six DOF.
- The math model has about 200 state variables, needed (along with parameters and configurable function definitions) to fully define the state of the system. These include the ODE variables plus others:
  - Each friction element has a state variable for hysteresis (suspension springs, steering system, low-speed tire steer).
  - Clutches and built-in controllers (e.g., ABS) have locked states.
  - 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

- CarSim 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.

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