Mechanical Simulation

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FMVSS 126 Electronic Stability Test and CarSim

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The United States National Highway Traffic Safety Administration (NHTSA) has established FMVSS 126, a new standard that will require all vehicles sold in the USA 4,536 Kg (10,000 pounds) or less to include an Electronic Stability Control (ESC) system as standard equipment starting in 2012 (phase in starting in 2010).[1]

This memo describes how the performance part of the testing required by FMVSS 126 is simulated with and without ESC controls in examples included in CarSim 7.1.

This is an updated version of a memo originally written September 2007 for CarSim 7.01.

Note Much of the FMVSS 126 procedure involves conditioning the vehicle and tires and accounting for testing and measurement variations that are not relevant for simulations. The conditioning and data processing portions of the standard are not covered in this memo.

Summary of the FMVSS 126 Test

After completion of a number of control checking and conditioning tests for the brakes and tires, FMVSS 126 requires three sets of tests. First is a "Slowly Increasing Steer Test" (S7.6). (S7.6 refers to the section in the standard.) Three tests are performed in which the vehicle is traveling at 80 km/h and the steering angle is ramped at 13.5 deg/s until a lateral acceleration of 0.5 g is reached; three similar tests are also done in the opposite direction (–13.5 deg/s to –0.5g). Data from the six tests are processed to determine the average steering wheel angle associated with a lateral acceleration of the vehicle mass center of 0.3 g. That steering wheel angle is designated ***A*** and is used to define and evaluate tests that follow.

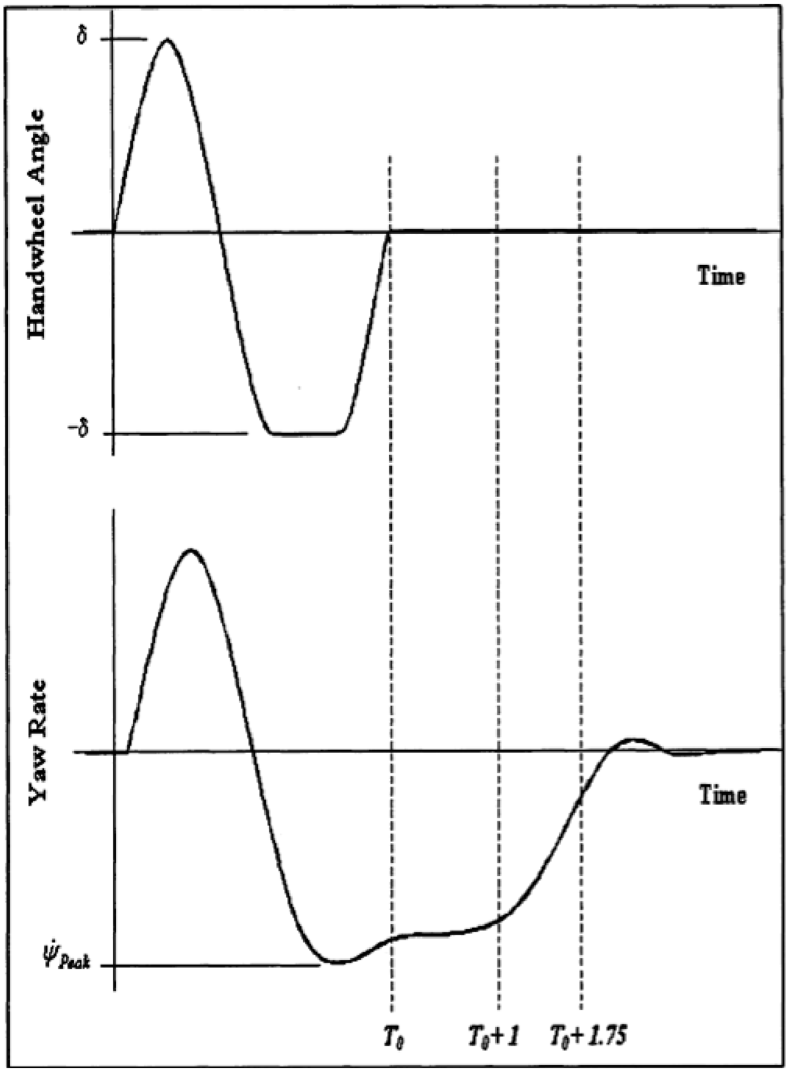

Figure 1. Steering wheel position and yaw rate are used to assess lateral stability.

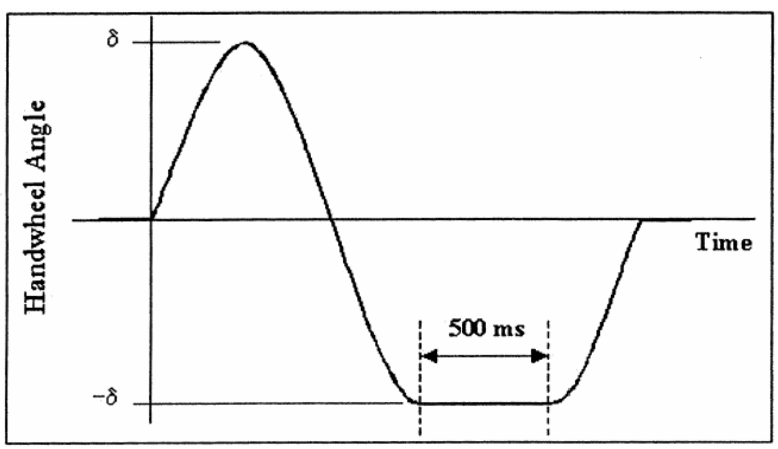

Figure 2. Sine with Dwell steering profile (p. 17315 from Federal Register).

Next, two series of “Sine with Dwell” tests are conducted with “a steering pattern of a sine wave at 0.7 Hz frequency with a 500 ms delay beginning at the second peak amplitude” (S7.9, see Figure 1 and Figure 2, copied from p. 17315 [1]). The sine amplitude δ is (Gain x ***A***), where the initial Gain is 1.5 (S7.9.3), and is increased for each test by an increment of 0.5 (S7.9.4) until the final run. The final run in a series is reached when the amplitude δ is greater than 270°. If the amplitude δ is greater than 300°, then the amplitude for the final run is reduced to 300° (S6.9.4).

The success or failure of each test in the series is based on the vehicle state at up to three times during the run (see Figure 3). A peak yaw rate is obtained by starting to scan the vehicle yaw rate when the steering wheel angle changes sign (0.71 sec after the Sine with Dwell starts).

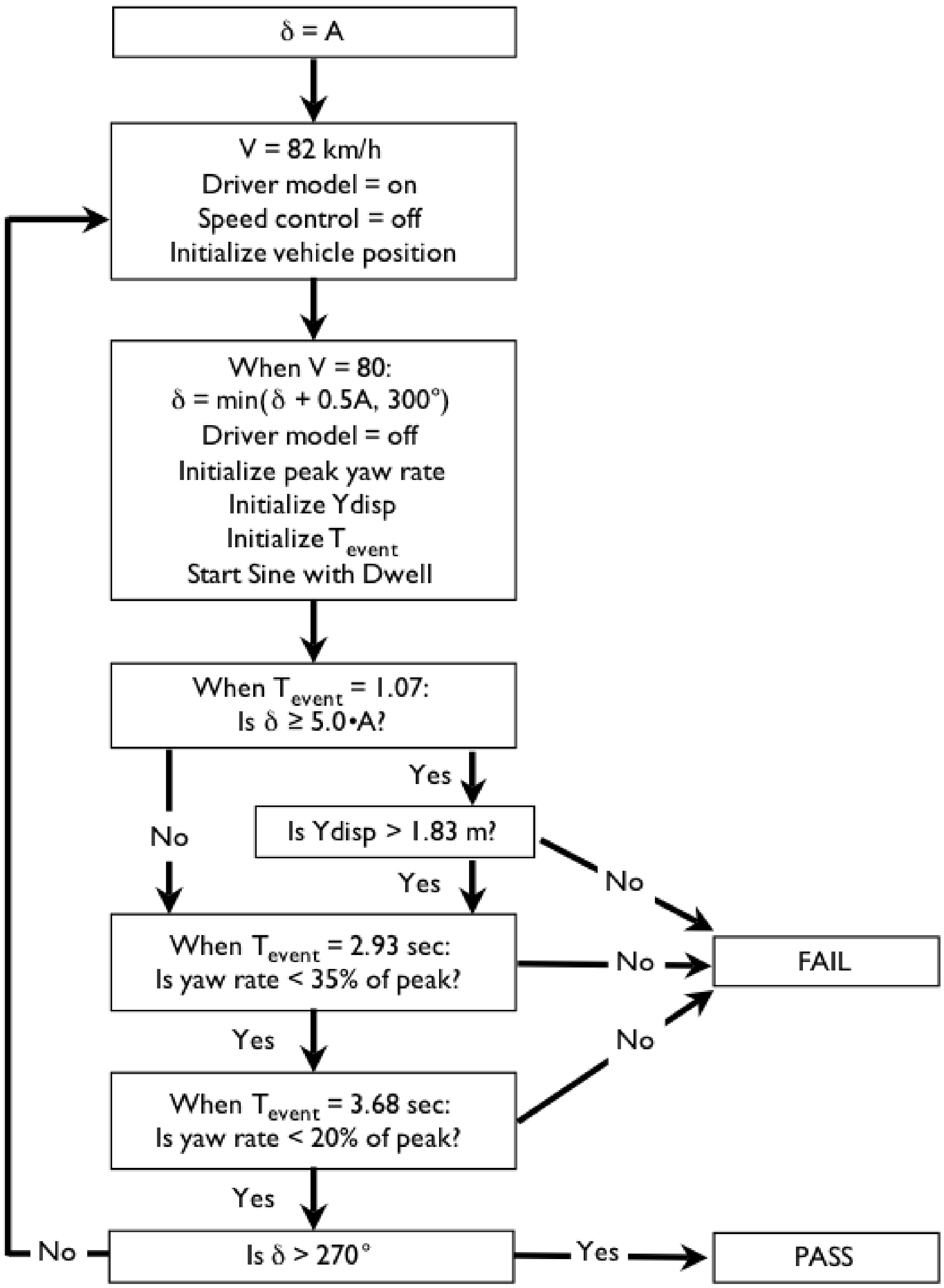

Figure 3. Flow chart for the Sine with Dwell test series.

1. At T = 1.07 sec (after the start of the Sine with Dwell), if the Gain is 5.0 or greater, then the lateral displacement of the vehicle mass center must be 1.83 m (6 ft) or greater relative to the start of the test for vehicles with GVW of 3,500 kg or less (S.5.2.3). If the displacement is less, then the vehicle fails the test. For vehicles with GVW greater than 3,500 kg, the required lateral displacement is 1.52 m (5 ft).
2. The instant yaw rate at T = 2.93 (1.0 sec after the steering stops) must be 35% of the peak rate or less (S5.2.1, see Fig. 1). If the instant yaw rate is higher than 35% of the peak yaw rate, then the vehicle fails the test.
3. The instant yaw rate at T = 3.68 (1.75 sec after the steering stops) must be 20% of the peak rate or less (S5.2.2, see Fig. 1). If the instant yaw rate is higher than 20% of the peak yaw rate, then the vehicle fails the test.

If the vehicle is tested to the final run in each direction and does not fail, then the vehicle passes the test.

Simulation of FMVSS 126 in CarSim

Most of the conditions covered by FMVSS 126 involve setting up the vehicle. This involves checking the electronics, conditioning the brakes, conditioning the tires, and making repeated tests to account for uncontrolled test variations. A typical CarSim model is set up with the vehicle properties (including tires and brakes) in the "ready to test" condition, so these steps are not necessary. Instead, the main interest is in setting up the sequence of Sine with Dwell tests, to allow a one-click run option to obtain a quick idea of how the simulated system would perform in the FMVSS 126 test.

In versions of CarSim prior to version 7, this sequence of tests might have been simulated with a batch of runs. Because the steering wheel amplitude depends on the result of the initial ramped steer tests (based on the steering wheel angle observed at $A_y = \pm 0.3$ g), different amplitudes are needed for every vehicle or configuration being simulated. The process would have to be adjusted by hand, or automated by combining CarSim with external software such as Simulink.

With the introduction of VehicleSim (VS) commands in CarSim 7.0, the entire sequence can be handled automatically in a single run. An example was posted on the www.carsim.com web site in September 2007, along with an earlier version of this memo.

Some improvements in the VS commands that are available in CarSim 7.1 have made the control simpler and more modular. To demonstrate this, CarSim 7.1 comes with example runs made with and without a simple ESC controller defined in Simulink. Using the controller, the vehicle passes the FMVSS 126; the same vehicle fails the test without the controller.

Events and Procedures

The sequences of test conditions are specified to set up a single run the covers the entire FMVSS 126 test sequence. This way, a link can be made to an **Events and Procedures** dataset (called an Events dataset in this memo) from the **Run Control** screen. An Events dataset defines one or more pending events. When triggered, information is loaded from new data files and the run continues. The sequence of controls and tests shown in Figure 3 is matched by a sequence of Event datasets. For example, Figure 4 shows the screen for the first Event dataset in the example.

This sets up the “Slowly Increasing Steer Test” for a positive ramp steer of 13.5 deg/sec, and will continue until the specified event condition is reached: A_y (lateral acceleration) reaching 0.3 g’s.

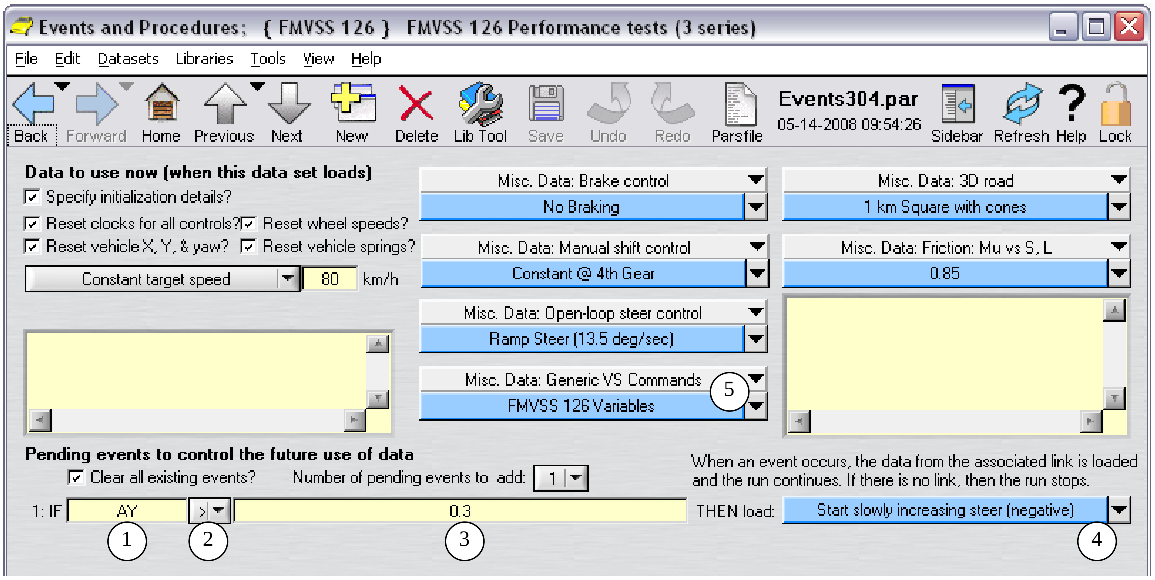

Figure 4. The first Event dataset for the FMVS 126 performance tests.

Events are defined by three or four pieces of information, as indicated by circled numbers in Figure 4. A variable 1 is compared 2 (the two options are ‘<’ and ‘>’) to an expression 3. If the expression includes any symbols (output variables, parameters, import variables, etc.), then the units of the expression and the variable are assumed to be in “internal dynamical units” (m, m/s^2, radian, etc.) in which no conversions are needed. On the other hand, if the expression 3 does not contain any symbols, as in the figure, then the units are assumed to be in “user display units” (those shown in output plots, echo files, and documentation). In the example figure, the “user display units” for A_y are g’s; therefore, the threshold of 0.3 g’s is specified with the number 0.3. As the run proceeds, the pending events are checked every time step. If the condition is satisfied (e.g., when $A_y > 0.3$ g), then the solver program reads data specified with the fourth element 4. In the example, the program would read data to define a slowly increasing steer in the other direction (ramp of –13.5 deg/sec). If there is no link specified for another dataset, then the run ends if the event is triggered.

The Sine with Dwell Steering Input

All of the Sine with Dwell tests use the open-loop steering waveform shown earlier in Figure 2, modified only by the scale factor δ. Figure 5 shows a CarSim dataset for an open-loop steering wheel angle using this waveform with a normalized amplitude of 1 radian (57.29… degrees). Figure 6 shows an **Events and Procedures** dataset that links to the Sine with Dwell waveform dataset 2 and provides additional context. This dataset is not loaded at the start of the run; it is loaded when an event is triggered to run a Sine with Dwell test.

As with most tables in CarSim, the table for steering wheel angle has a corresponding time offset parameter that can adjust the time used in the table relative to absolute simulation time. As shown in the figure, the input to the table is the quantity `T-TSTART_STEER`.

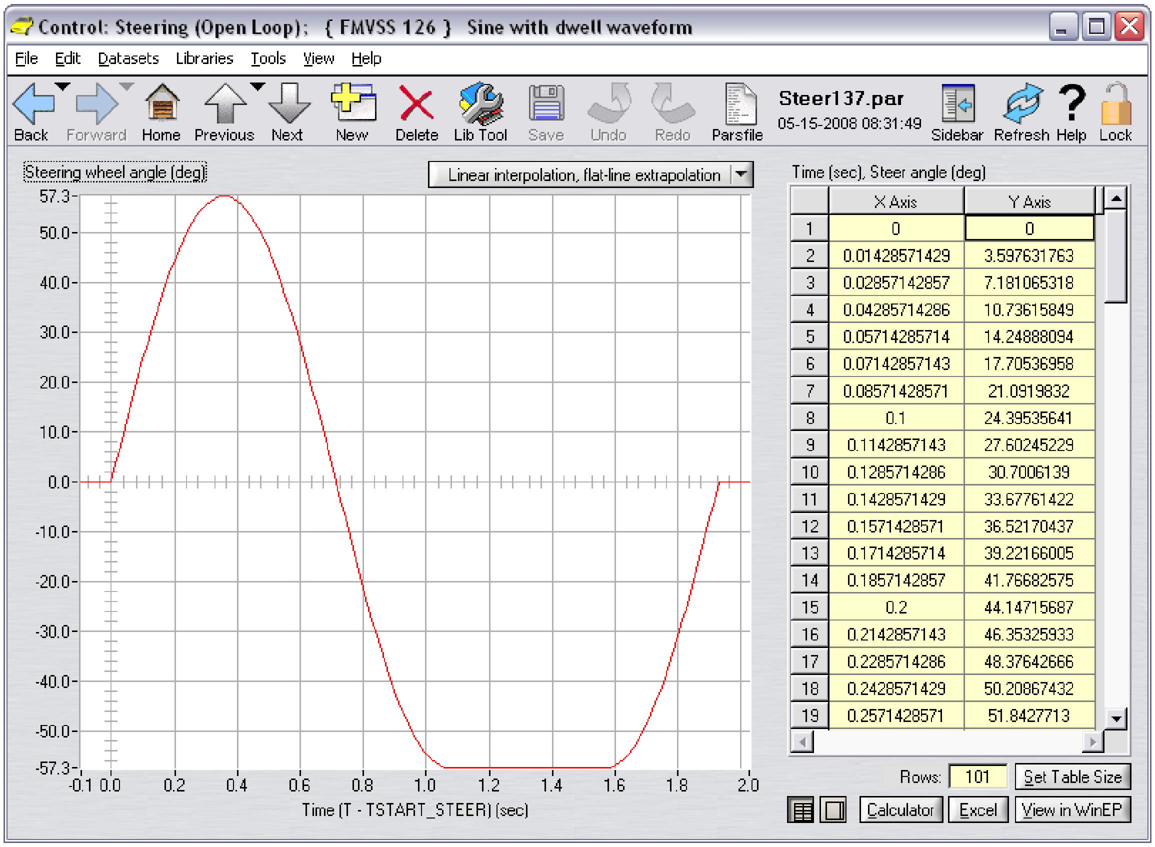

Figure 5. Sine with Dwell waveform, with amplitude = 1 radian (57.29… deg).

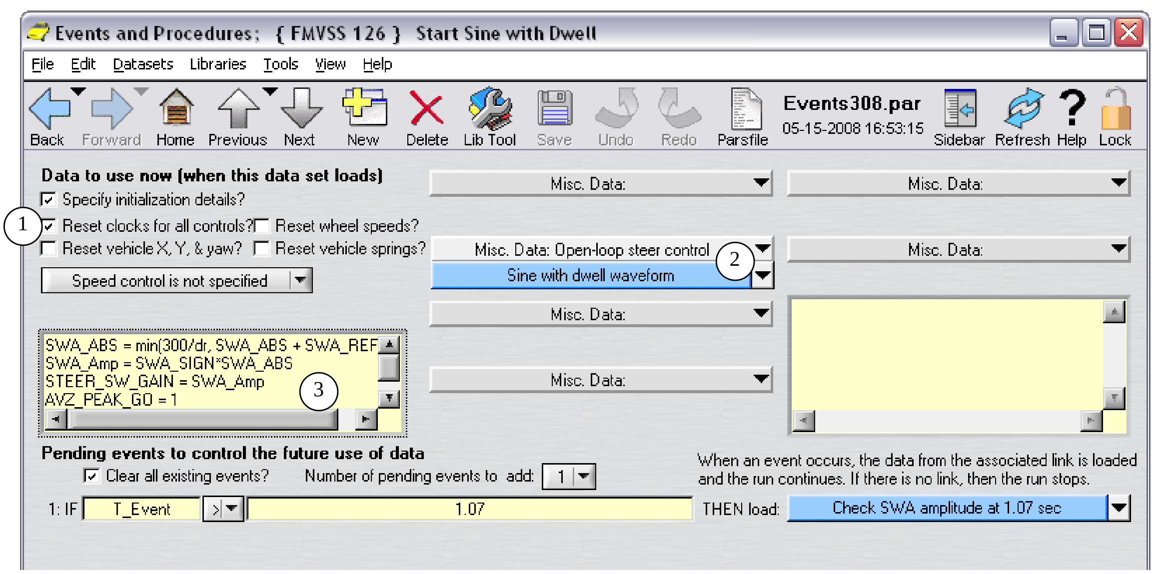

Figure 6. Dataset for starting a Sine with Dwell test.

The box ① (Figure 6) is checked to reset the clock for all open-loop controls when this dataset is loaded at some point during the run. For example, if the absolute simulation time is 22.1 seconds when an event it triggered to cause the dataset shown in Figure 6 to load, then TSTART_STEER is set to 22.1 and the Sine with Dwell waveform will start with a local time value (T – TSTART_STEER) of zero.

The **Events and Procedures** dataset (Figure 6) also sets the gain for the Steer with Dwell waveform using symbolic expressions 3 that are repeated in Listing 1.

Listing 1. Setting new values for steering wheel amplitude with symbolic expressions.

```
SWA_ABS = min(300/dr, SWA_ABS + SWA_REF/2)
SWA_Amp = SWA_SIGN*SWA_ABS
STEER_SW_GAIN = SWA_Amp
AVZ_PEAK_GO = 1
```

In the listing, SWA_REF is a reference angle determined by the initial ramp steer tests, DR is a scale factor to convert degrees to radians, SWA_ABS is the absolute value of the gain, SWA_SIGN is 1 or -1, and STEER_SW_GAIN is the gain parameter associated with the table of steering wheel angle as an open-loop function of time.

Note The VS solvers in CarSim work with two units systems: internal units are dynamically consistent and have all angles in radians; user-display units use scale factors to read and display more convenient units, such as degrees for angles (see Figure 5).

When values are assigned to variables using symbolic equations, any numerical values must be provided in internal units. For example, in the equation above, the limit of 300 degrees for SWA_ABS is divided by DR to convert to radians.

More information about the units systems is provided in the VS Solvers Reference Manual [2].

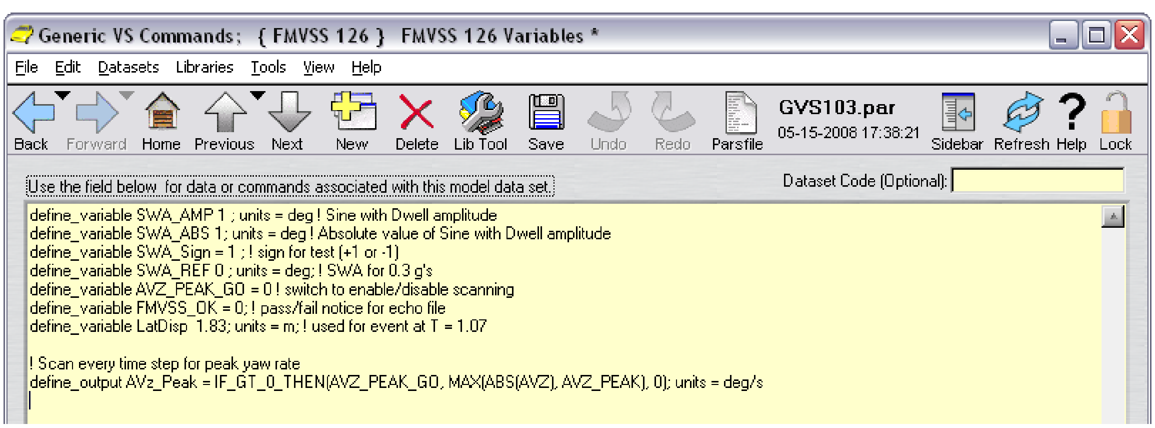

Figure 7. VS Commands to install new variables in CarSim for the FMVSS 126 procedure.

Variables added to CarSim with VS Commands

The test sequence describes several additional variables that are not standard in CarSim, but which can be added using VS commands [2]. Figure 7 shows a dataset that introduce new variables in CarSim to support the FMVSS 126 test procedure using the VS commands shown again in Listing 2, with line numbers inserted. The dataset is linked to the first **Events and Procedures** dataset (5 in Figure 4), to introduce the new variables at the start of the simulation run using the VS commands `define_variable` and `define_output`.

Listing 2. VS commands to define new variables.

```
1.   define_variable SWA_AMP 1 ; units = deg ! Sine with Dwell amplitude
2.   define_variable SWA_ABS 1; units = deg ! Absolute value of SWA_AMP
3.   define_variable SWA_Sign = 1 ; ! sign for test (+1 or -1)
4.   define_variable SWA_REF 0 ; units = deg; ! SWA for 0.3 g's
5.   define_variable AVZ_PEAK_GO = 0 ! switch to enable/disable scanning
6.   define_variable FMVSS_OK = 0; ! pass/fail notice for echo file
7.   define_variable LatDisp 1.83; units = m; ! used for event at T =
               1.07
8.
9.   ! Scan every time step for peak yaw rate
10.  define_output AVz_Peak = IF_GT_0_THEN(AVZ_PEAK_GO, MAX(ABS(AVZ),
               AVZ_PEAK), 0); units = deg/s
```

Note that some of the variables described in the previous subsection (`SWA_REF`, `SWA_ABS`, and `SWA_SIGN`) are introduced in Listing 2 (lines 2 - 4). In addition to these variables, a new output variable `SWA_Amp` is added for use in event conditions later on to determine whether the limits of ±270° have been reached (line 1).

Two of the pass/fail evaluations in the Sine with Dwell test are based on the peak yaw rate (`AVZ_PEAK`), defined with an equation that uses another variable (`AVZ_PEAK_GO`) to enable or disable scanning (lines 5, 10).

Another evaluation involves the lateral tracking of the vehicle center of mass. A new parameter is introduced (`LatDisp`) (lines 7) for the tracking requirement.

The Test Sequence

The example test sequence included with CarSim 7.1 uses 13 Event datasets. They are summarized below in the order in which they are encountered. Each Event dataset also includes documentation notes with more detail.

1. **FMVSS 126 Performance tests (3 series).** This is the Event dataset shown in Figure 4 that is linked from the Run screen. It sets up initial conditions, adds some variables to the CarSim model using VS commands (the linked dataset 5 shown in Figure 7), and monitors lateral acceleration in order to load the next dataset when Ay > 0.3g.
2. **Start slowly increasing steer (negative).** This saves the current steering wheel angle, resets the vehicle, and starts a test with a steering ramp of –13.5 deg/s. It loads the next dataset when Ay < –0.3g.
3. **Set reference steer angle and start first series**. This sets `SWA_REF` to the average absolute steering associated with tests going to +0.3 g and –0.3g. It sets `SWA_ABS` to `SWA_REF`, `SWA_SIGN` to +1, and proceeds to the next dataset.
4. **Prepare for Sine with Dwell**. The Sine with Dwell test requires open-loop steering (provided in physical testing by a robot), with the vehicle coasting down in high gear from 80 km/h. To set the vehicle up in a steady condition, this dataset resets the vehicle

to a speed of 82 km/h, at the center of the road (Y = 0, Yaw = 0), with the driver path follower model engaged. It will load the next dataset when speed drops to 80 km/h.

5. **Start Sine with Dwell.** This is the Event dataset shown in Figure 6 that was described previously. The steering amplitude is incremented by 0.5•SWA_REF. If the amplitude is more than 300° then it is limited to 300°. Monitoring of the yaw rate is enabled, to start updating the AVZ_PEAK variable. The local time is reset (T_Event = 0, TSTART_STEER = T) for the Sine with Dwell waveform and for tracking the next few events. Control is switched to open loop (the Sine with Dwell waveform). The next dataset will be loaded when T_Event reaches 1.07 sec.

6. **Check SWA amplitude at 1.07 sec**. The steering amplitude is compared to 5•SWA_REF. If greater than or equal to this level, it loads the dataset **Check Lat Disp (greater than 1.83?)**. Otherwise it loads the dataset **Continue to 2.93 sec**.

7. **Check Lat Disp (greater than 1.83?)**. This sets up two event conditions. If LatDisp < 1.83, the vehicle fails and a dataset is loaded with the name: **This vehicle FAILED the test**. Otherwise it loads the next dataset.

8. **Continue to 2.93 sec.** This sets up an event for 2.93 sec (1.0 sec after the Sine with Dwell waveform stopped). When this occurs, it loads the next dataset.

9. **Check yaw rate at 1 sec (2.93 sec)**. This sets up two events. If the absolute yaw rate is more than 35% of the peak absolute yaw rate then the vehicle fails and the dataset is loaded with the name: **This vehicle FAILED the test**. The other event is triggered when the clock reaches 3.68 seconds, at which time the next dataset is loaded.

10. **Check yaw rate at 1.75 sec (3.68 sec)**. The sets up four events to determine what to do next (See Figure 8). The first new event checks the current yaw rate, which must be less than 20% of the peak. If not, the dataset is loaded with the name: **This vehicle FAILED the test**. If the yaw rate was OK, then three checks are made to determine what kind of test to do next. If SWA_Amp < –270°, then this was the final test, the vehicle passed, and the dataset is loaded with the name: **The vehicle PASSED the test**. If SWA_Amp > 270°, then this is the final test in the first series of Sine with Dwell tests and the next dataset is loaded to start the second series. Otherwise, this was not the final test in the series, so the next test is started by loading the **Prepare for Sine with Dwell** dataset again (dataset 4 in this list).

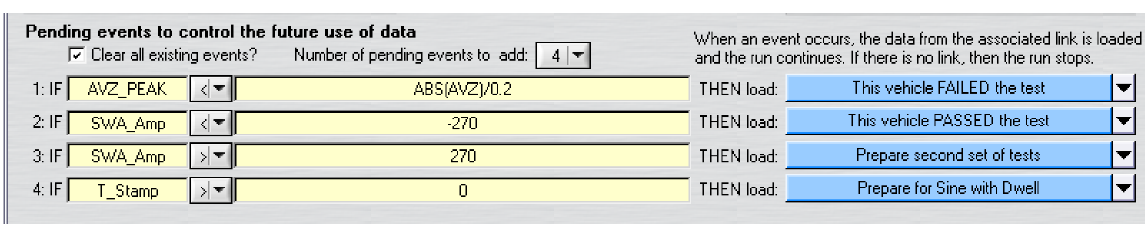

Figure 8. Events set in the dataset: Check yaw rate at 1.75 sec (3.68 sec).

11. **Prepare second set of tests**. This is similar to dataset 3, **Set reference steer angle and start first series**. SWA_ABS is set to SWA_REF again. This time, SWA_SIGN is set to –1. It immediately loads dataset 4, **Prepare for Sine with Dwell**.

12. **This Vehicle FAILED the test**. All titles of event datasets are recorded into the Log file when a run is made. When this dataset is loaded, the run ends with this title. Also, the variable `FMVSS_OK` is given a value of 0, which appears in the echo file made at the end of the run.
13. **This Vehicle PASSED the test**. When this dataset is loaded, the run ends with this title. Also, the variable `FMVSS_OK` is given a value of 1.

Example Results

The example dataset in CarSim 7.1 uses a large SUV vehicle with a simple ESC controller defined in Simulink to use the brakes when needed to maintain stability.

Figure 9 shows some plots made from the simulation. The two on the left side show responses as functions of local time, with the appearance of many repeated tests. The others show responses as functions of absolute time.

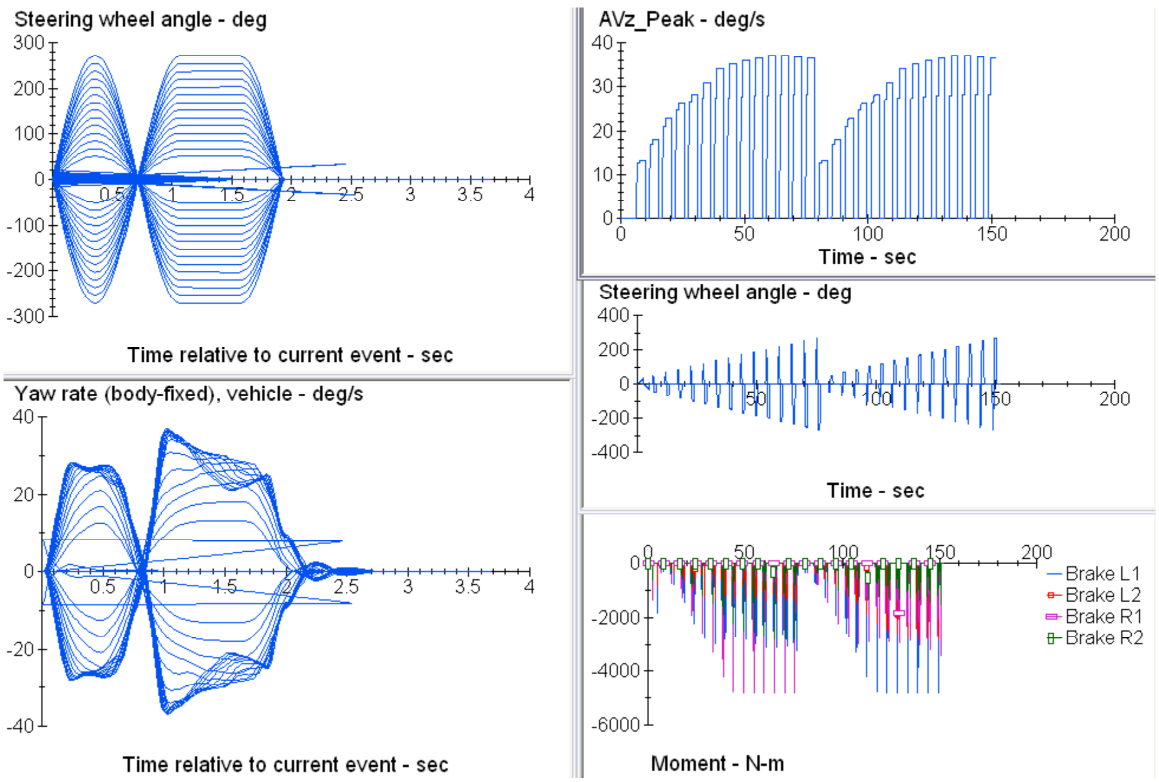

Figure 9. Response of the vehicle with ESC for the full test sequence.

Listing 3 shows the end of the log file generated with the run. The log file lists every dataset that was used and logs each event that is triggered. Notice that title for the last dataset that was used (shown in bold) indicates that the vehicle passed the test.

Listing 3. End of log file for vehicle with ESC controller.

```
Event encountered at t = 152.352: SWA_AMP < -270 deg
Include PARSFILE "C:\Product_Working\CarSim71_Data_08_05_14\Events\Events315.par"
Used Dataset: Events and Procedures; { FMVSS 126 } This vehicle PASSED the test

Event encountered at t = 152.353: T_STAMP > 0 sec

Run stopped: Event encountered with no continuation parsfile at T = 152.353
```

Listing 4. Portion of the echo file written at the end of the run with an ESC controller.

```
!------------------------------------------------------------------------------
! NEW VARIABLES DEFINED AT RUN TIME
!------------------------------------------------------------------------------
DEFINE_VARIABLE SWA_A = 1;
DEFINE_VARIABLE SWA_ABS = 4.74632;
DEFINE_VARIABLE SWA_SIGN = -1;
DEFINE_VARIABLE SWA_REF = 33.993; UNITS = deg;
DEFINE_VARIABLE AVZ_PEAK_GO = 1;
DEFINE_VARIABLE FMVSS_OK = 1;
DEFINE_VARIABLE LATDISP = 1.73117; UNITS = m;
DEFINE_OUTPUT SWA_Amp = 0; UNITS = deg;
DEFINE_OUTPUT AVz_Peak = 0; UNITS = deg/s;

!------------------------------------------------------------------------------
! EQUATIONS OUT (AT END OF EACH TIME STEP)
!------------------------------------------------------------------------------
EQ_OUT SWA_AMP = SWA_ABS*SWA_SIGN ;
EQ_OUT AVZ_PEAK = IF_GT_0_THEN(AVZ_PEAK_GO, MAX(ABS(AVZ), AVZ_PEAK), 0) ;
EQ_OUT LATDISP = ABS(YCG_TM) ;
```

Listing 4 shows a portion of the echo file written at the end of the run, with the values of the new variables added with VS commands, including `FMVSS_OK` with a value of 1 (passed).

Figure 10 shows the steering and yaw rate response for the same vehicle without ESC, that fails when the yaw rate at 2.93 sec (1.0 sec after the steering input stops) is not less than 35% of the peak. Listing 5 shows a few lines near the end of the log file that document how the failure occurred.

Listing 5. Part of the log file for the vehicle that failed the test.

```
Used Dataset: Events and Procedures; { FMVSS 126 } Check yaw rate at 1 sec (2.93 sec)

Event encountered at t = 30.562: AVZ_PEAK < 100.14 deg/s
Include PARSFILE "C:\Product_Working\CarSim71_Data_08_05_14\Events\Events311.par"
Used Dataset: Events and Procedures; { FMVSS 126 } This vehicle FAILED the test
```

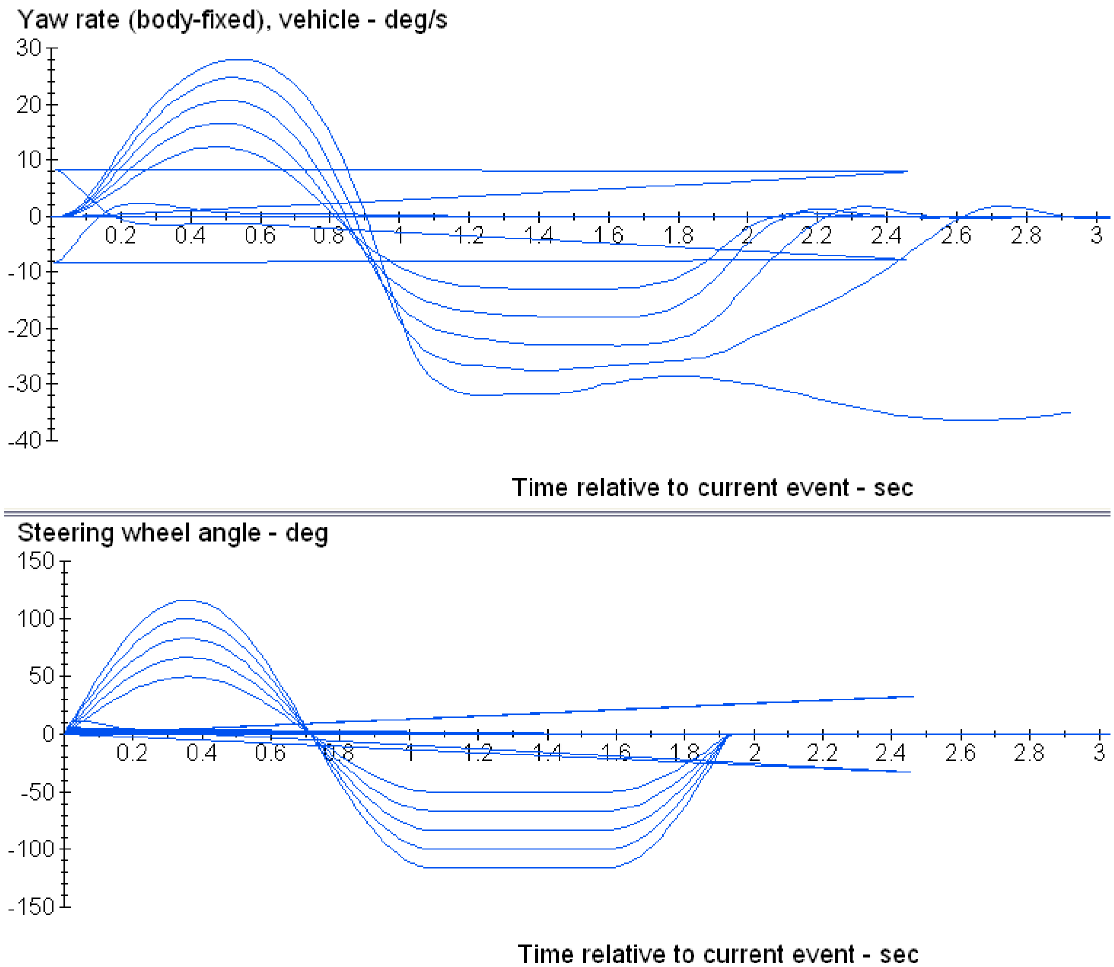

Figure 10. Response of the vehicle without ESC (failure).

Limits and Assumptions

The FMVSS 126 standard describes a physical testing procedure. Many of the methods and procedures involve checking electronics, conditioning the vehicle and tires, and accounting for the inevitable variations that occur in a testing environment. The example dataset described in this memo does not attempt to cover many of the details involving instrumentation and data processing used in physical testing. Several aspects of the performance testing require careful work in testing, but are very easy to apply in simulation if shortcuts are taken.

One shortcut was taken in determining the reference angle ***A***, designated `SWA_REF` in the simulations. FMVSS 126 specifies that six tests be run, with the results processed using linear regression to relate steering wheel angle to lateral acceleration (A_y). The intent is to reduce the effects of measurement noise and test-to-test variation. Because these factors do not exist in the CarSim world, we run just two tests and simply stop when A_y reaches limits of ±0.3g.

Another shortcut involves the definition of the lateral displacement of the vehicle mass center. Due to the expense of an automated instrumentation package that can measure absolute X and Y coordinates, the standard encourages calculation of lateral displacement by calculating A_y (removing vehicle roll and pitch effects from accelerometer measurements) and doubleintegrating it. Although it is close, this is not exactly the same as true lateral position due to the interaction with yaw during the test. This possibly complicated data processing method was eliminated in the example by setting up the vehicle at the start of each Sine with Dwell test such that the yaw and lateral displacement were essentially zero.

One final shortcut worth mentioning is that the transition from test to test was done abruptly, because it reduces the time needed to finish the run. When the simulation is done 100% with software, this is an efficient approach. However, if this example procedure is used in a real-time HIL system with physical electronic controllers, abrupt changes in vehicle speed or steering wheel angle might trigger failure detectors. In this case, transition events should be inserted to proceed from one stage to the next while maintaining continuity, as expected with physical testing.

References

1. Federal Register, Vol 72, No. 66, April 6, 2007, pp 17310-17315, Part 571.126.

2. VehicleSim Math Models: Solver Program Reference Manual, Mechanical Simulation, Ann Arbor, MI, USA, May 2008. (Also available from www.carsim.com)