Mechanical Simulation

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Electronic Stability Control (ESC)

CarSim and TruckSim include a simple electronic stability controller (ESC) that applies individual brakes to avoid loss of vehicle control by generating a correcting yaw moment. All brakes on the lead vehicle are applied by the controller. If trailers are part of the vehicle combination their brakes are not applied by the controller, however the end-user may extend the controller with VS Commands to achieve this. VS Commands are described in the *VS Commands Reference Manual* (Help > Reference Manuals) and require no additional software.

Introduction

Governments throughout the world have instituted regulations mandating that vehicles be equipped with ESC or requiring them to meet performance standards that are designed to be unachievable by vehicles without ESC. For example, the United States government standard FMVSS 126 and the equivalent European Union ECE regulation 13H both use a test process called "Sine with Dwell" to confirm that the vehicle being tested has a functioning ESC system. Applicable to passenger cars and light trucks, CarSim includes a Sine with Dwell example in the shipping database. Commercial vehicles in the United States are subject to FMVSS 136, a stability control test consisting of a half circle, 150 feet in diameter. An example of this road is included in the TruckSim database.

Function of an Electronic Stability Control System

Electronic Stability Control systems are intended to provide a primarily yaw control mechanism by applying individual wheels brakes. ESC is commonly extended with other vehicle controls such as engine torque reduction and torque vectoring to achieve the desired yaw correction. Originally intended to address oversteer cases in rear-wheel drive cars on low mu surfaces, modern ESC systems operate over a wide range of road surface conditions and help mitigate both oversteer and understeer situations. For oversteer cases, the largest amount of brake pressure is applied to the outside front tire; some control strategies also apply a small amount of brake pressure to the remaining brakes, thus slowing the vehicle down without inducing more yaw instability. For understeer cases, the primary brake is the inside rear wheel.

An extension of ESC is rollover stability control. In this case, additional vehicle-mounted sensors are used to detect a rollover condition. As with ESC, rollover stability control systems apply individual wheel brakes and possibly reduce engine torque, torque vectoring, etc., but to a much greater degree than ESC such that momentary wheel lock of the outside front tire is intentional. The momentary locked tire reduces the lateral force, and thus the roll moment generated by that tire. In SUVs, vans, and commercial vehicles operating on high mu surfaces, roll instability is commonly induced before yaw instability, so the rollover stability control will typically engage before an ESC system.

Installing the Controller

By default, the controller is not installed in a CarSim or TruckSim example. To install and use the controller, link to a dataset from the **Control: Electronic Stability (ESC)** library. Any dataset from this library will apply the VS Command `INSTALL_ESC` to install the controller for the run along with associated parameters and variables. Figure 1 shows how the parameters appear in an Echo file when the ESC is installed and activated by the parameter `OPT_ESC_ON` (whose default value is 1, indicating that the controller is on).

The Echo file shown in Figure 1 lists all available ESC parameters. Two of the parameters are calculated but are shown to provide more information (`STEER_RATIO_ESC` and `WB_ESC`). The others are used to adjust the behavior of the ESC, as described in the next section.

Output variables generated by the controller are described later (page 5), as are the equations used by the controller (page 6).

The Brake System screens in CarSim and TruckSim include a drop-down menu and yellow data fields for the internal ABS system. In order for the built-in ESC to work:

1. Internal ABS is enabled.
2. Two channel control is selected. Single channel ABS modulates both wheels of an axle together and defeats the yaw rate control of an ESC.

The Control: Electronic Stability (ESC) screen

The **Control: Electronic Stability (ESC)** screen (Figure 2) has ten fields for specifying values for the ESC parameters. Every Parsfile from this library has the command `INSTALL_ESC`, installing the controller with the on/off state set on (`OPT_ESC_ON` = 1).

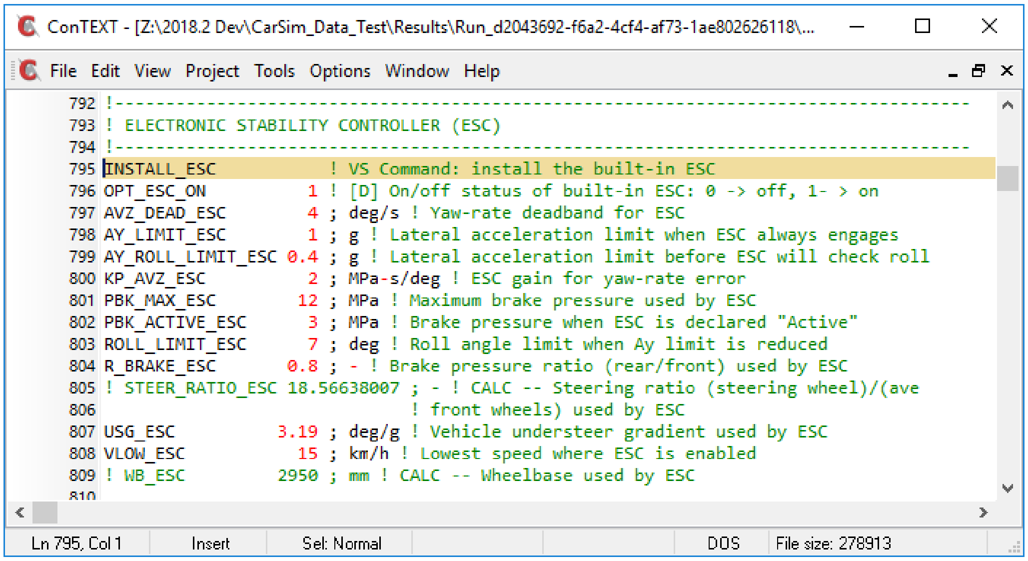

Figure 1. Parameters for the built-in ESC.

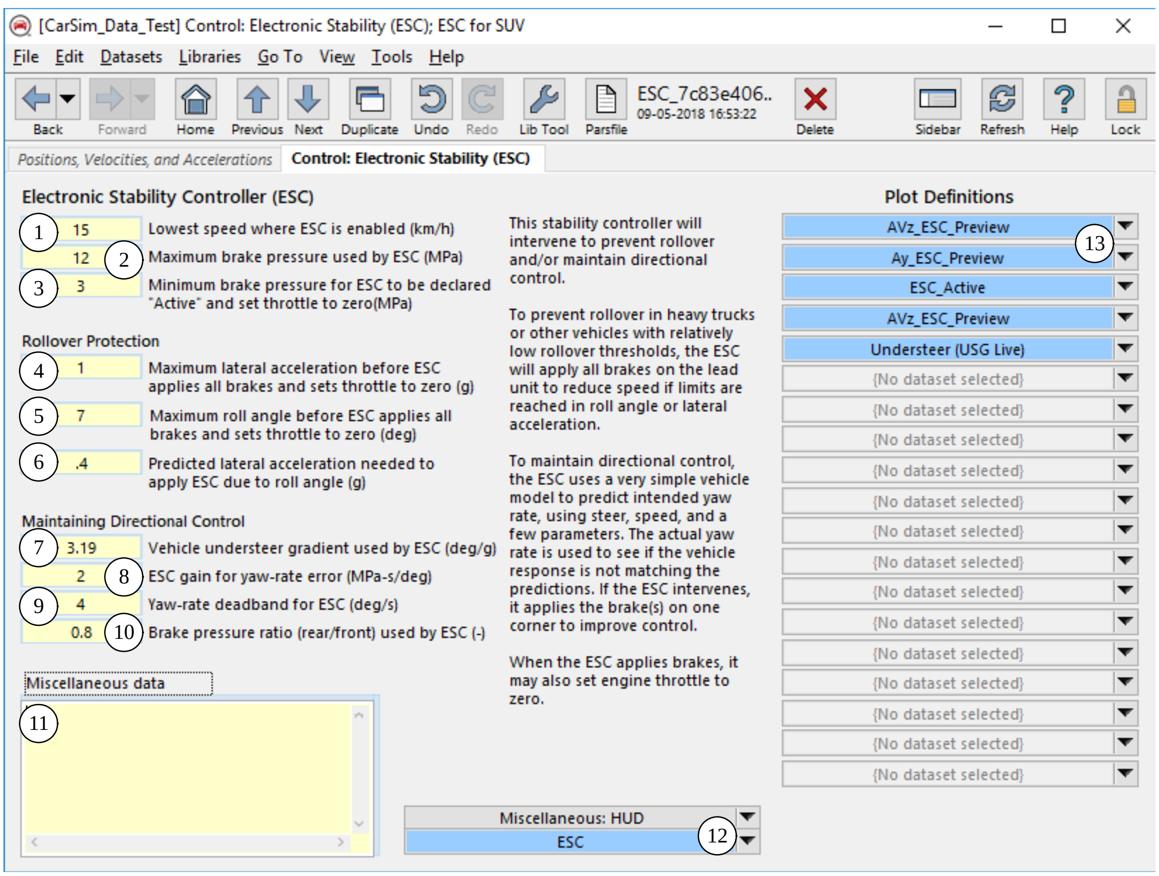

Figure 2. Control: Electronic Stability (ESC) screen.

The screen has fields for the ten parameters of the ESC, plus controls for VS Commands, animation support such as a HUD dataset to show an ESC alert when the controller is active, and links for relevant plots.

System Controls

① Lowest speed for enabling ESC (keyword = VLOW_ESC). The ESC is automatically disabled if the transmission is in reverse, or if the forward speed is less than the limit VLOW_ESC.

② Maximum brake pressure used by ESC (keyword = PBK_MAX_ESC). This pressure will be used on all wheels when at risk of rollover. When the brakes are applied to maintain directional control, the pressure will never be set higher than this limit.

③ Minimum brake pressure in which the ESC is considered "Active" (keyword = PBK_ACTIVE_ESC). When the brake pressure requested by the ESC is larger than this limit, the system is considered "Active" and the engine throttle is automatically set to zero. The "Active" state is provided by the output variable ESC_Active, which may be used to show a HUD alert in VS Visualizer.

> **Note** The ESC's ability to apply brake pressure is not limited to the minimum brake pressure defined by PBK_ACTIVE_ESC. For example, a yaw control correction may be calculated (see page 9) and the necessary brake pressure will be applied to the appropriate wheel or wheels. If this pressure is less than PBK_ACTIVE_ESC, ESC_Active will still be zero, the throttle will not be set to zero, and the ESC HUD icon will not light up. This is a common strategy to avoid what are sometimes called nuisance warnings.
>
> Setting PBK_ACTIVE_ESC to zero means ESC_Active will report 1 for every ESC activation. Here, the throttle will also be set to zero for every activation, even activations requiring only a small amount of brake pressure.

Rollover Protection

④ Maximum allowed lateral acceleration before the ESC applies brakes to slow down (keyword = AY_LIMIT_ESC). Brakes are applied and the throttle is disabled if the lateral acceleration exceeds this limit. For heavy trucks, set this to be a little less than the rollover threshold. Note that if this is set higher than the vehicle's lateral acceleration limit, this will have the effect of disabling the ESC's check for this condition.

⑤ Maximum allowed roll angle before the ESC applies brakes to slow down (keyword = ROLL_LIMIT_ESC). Brakes are applied and the throttle is disabled if the roll angle exceeds this limit and there is some steering ⑥. For heavy trucks, set this to be a little less than the rollover threshold. Note that if this is set higher than the vehicle's roll limit, this will have the effect of disabling the ESC's check for this condition.

⑥ Minimum predicted lateral acceleration needed to apply full braking in case of imminent rollover as determined by the vehicle roll angle reaching the roll limit ⑤ (keyword = AY_ROLL_LIMIT_ESC). Use for heavy truck rollover protection. ESC will not intervene for rollover protection unless the lateral acceleration predicted for the current steering wheel angle is above this limit.

Maintaining Directional Control

(7) Understeer gradient used by the ESC to predict yaw rate and lateral acceleration (keyword = `USG_ESC`). Understeer gradient used by ESC to predict yaw rate for a given steering wheel angle and speed, as described in a later section (page 6).

In general, there are multiple methods for defining an understeer gradient which provide substantially different values for the vehicle. This parameter should be given a value that is consistent with the equations used by the ESC. To aid in obtaining a value, an output variable `USC_Live` is provided by the ESC to calculate understeer using the same definition, and uses current values of steering, speed, wheelbase, and yaw rate.

The ESC also provides output variables for predicted angular velocity (`AVz_ESC_Pre`) and lateral acceleration (`Ay_ESC_Pre`) which may be compared with the vehicle yaw rate `AVz` and lateral acceleration `Ay_Rd` (relative to the road surface).

(8) Gain applied by controller to set brake pressure to improve directional control (keyword = `KP_AVZ_ESC`). This is the ratio of brake pressure from ESC per unit of yaw-rate error. See the ESC equations for details (page 6).

(9) Yaw-rate deadband (keyword = `AVZ_DEAD_ESC`). The controller equations allow for some difference between the predicted yaw rate and actual yaw rate (the deadband) before intervention is applied.

(10) Brake pressure ratio, rear/front (keyword = `R_BRAKE_ESC`). Brake pressures for axle 1 are calculated using the specified gain (8). Pressures for other axles are calculated by multiplying the front pressure by this ratio.

If the vehicle unit has more than two axles, the same pressure is applied to all. In these cases, `R_BRAKE_ESC` can be reduced to maintain balance.

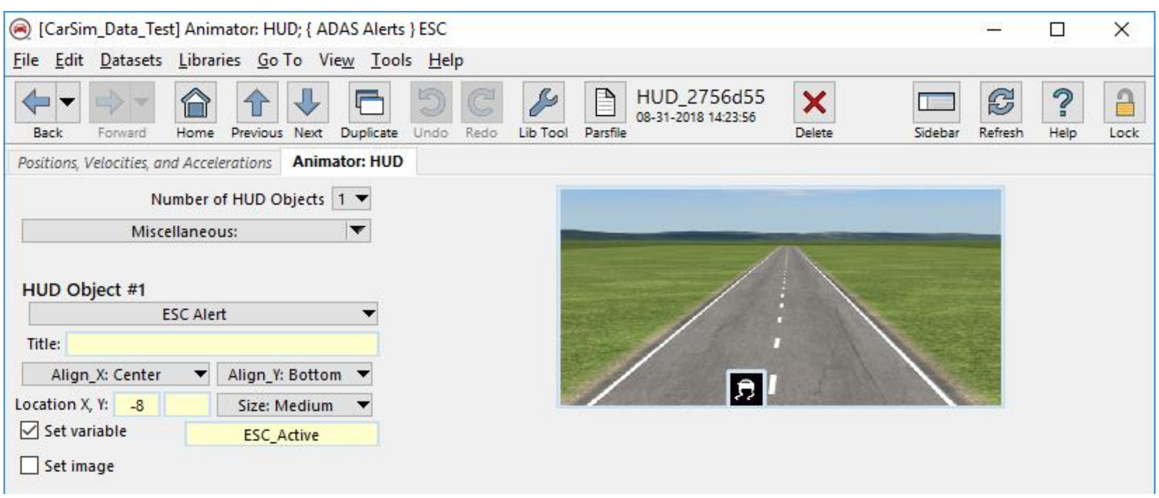

Figure 3. Animator HUD dataset to show ESC icon when active.

Miscellaneous Controls

(11) Miscellaneous yellow field, used for writing VS Commands to extend the controller.

(12) Miscellaneous link, used in the example for an animator dataset to show an ESC alert when the ESC is in "Active" mode. In this example, the ESC Alert is made visible by the output variable ESC_Active (Figure 3).

(13) Links to **Plot Setup** datasets for ESC-related plots.

Output Variables

Table 1 lists output variables associated with the ESC. These are used in the equations presented in the next section.

Table 1. Output variables for the built-in ESC.

Name	Units	Description
AVz_ESC_Err	deg/s	Error in ESC yaw-rate prediction
AVz_ESC_Lin	deg/s	Linear prediction of yaw-rate
AVz_ESC_Pre	deg/s	ESC prediction of yaw-rate
Ay_ESC_Pre	g	Ay predicted for ESC
ESC_Active	-	ESC is active (braking is being applied)
ESC_Enabled	-	ESC is enabled
Mu_ESC	-	Average Mu over all tires on lead unit
PbkESC_L1	MPa	Delivery pressure from ESC, L1 wheel
PbkESC_R1	MPa	Delivery pressure from ESC, R1 wheel
PbkESC_L2	MPa	Delivery pressure from ESC, all left rear wheels
PbkESC_R2	MPa	Delivery pressure from ESC, all right rear wheels
SteerESC	deg	Average front steer used by ESC
USG_Live	deg/g	Understeer gradient calculated "live" from vehicle steer, speed, wheelbase, and

Control Logic

The ESC is installed with the command INSTALL_ESC. If not installed, it is not included in the simulation.

When the ESC is Enabled

When installed, the ESC is enabled under these conditions:

1. The parameter OPT_ESC_ON is set to a non-zero value. (This is the default after the INSTALL_ESC command is applied.)
2. The transmission is not in reverse.
3. The forward vehicle speed is greater than the threshold specified by the parameter VLOW_ESC.

The Enabled/Disabled status of the controller is available from the output variable ESC_Enabled.

When enabled, the ESC can send commands to all of the brakes on a single-unit vehicle, or the lead unit of a vehicle with trailer(s).

The ESC provides four pressure requests. `PbkESC_L1` and `PbkESC_R1` are brake delivery pressures for the two front wheels. As described in the *Brake System* Help document, the delivery pressure is after any proportioning, and before the built-in ABS controller.

The pressure request `PbkESC_L2` is applied to all other left wheels on the vehicle unit. For CarSim, this is the single left-rear wheel. For TruckSim, it might apply to multiple wheels if the vehicle has more than two axles. The pressure request `PbkESC_R2` is applied to all right rear wheels behind axle 1.

If any of pressure requests are greater than a threshold specified by the parameter `PBK_ACTIVE_ESC`, then the ESC is considered “Active” and the output variable `ESC_Active` is set to 1; otherwise it is zero. When `ESC_Active` is nonzero, the powertrain model overrides the engine throttle, setting it to zero. In some examples, `ESC_Active` is used to control the visibility of an alert in VS Visualizer.

ESC Logic

When enabled, the ESC will intervene for two reasons: (1) risk of rollover, and (2) loss of control.

In both cases, the ESC uses the current steering and speed to predict how much the vehicle should be turning using simple calculations.

Predicting yaw rate and lateral acceleration

The ESC estimates the intended yaw rate using the current steering wheel angle and forward speed.

An effective steering ratio `STEER_RATIO_ESC` between the average of the front wheels and the steering wheel is calculated during initialization, using derivatives of the Configurable Functions that apply for the type of steering (rack and pinion or recirculating ball). This calculated property is listed in the Echo file with ESC parameters (Figure 1, page 3).

> **Note** `STEER_RATIO_ESC` is an idealized ratio and does not take compliances of the steering system and suspensions into account.

Each time step of the CarSim and TruckSim simulation, the ESC calculates the average of the front wheels `SteerESC` as:

$$\mathtt{SteerESC} = \mathtt{Steer\_SW} \ / \ \mathtt{STEER\_RATIO\_ESC} \quad (1)$$

where `Steer_SW` is the steering wheel angle and `SteerESC` is an output variable.

The ESC also calculates a wheelbase `WB_ESC` during initialization by averaging the `LX_AXLE` parameters for all rear suspensions of the lead unit (or simply `LX_AXLE` for axle 2 if the vehicle unit has only two axles) and subtracting `LX_AXLE` from axle 1 (i.e., `LX_AXLE(2)` – `LX_AXLE(1)`; in CarSim, the default value of `LX_AXLE(1)` is zero). This calculated property is also listed in the Echo file (Figure 1).

The controller predicts a yaw rate AVz_ESC_Lin (an output variable) that is linearly related to steer:

$$\text{AVz\_ESC\_Lin} = \text{SteerESC*V} / (\text{WB\_ESC + USG\_ESC*V}^2) \tag{2}$$

where V is the forward speed, and USG_ESC is an ESC parameter that is an estimate of the vehicle understeer gradient.

The understeer parameter USG_ESC is critical to the validity of equation 2. As noted earlier in the description of the parameter (page 5), an output variable USC_Live is provided by the ESC to help determine a useful value for USG_ESC. The live understeer USC_Live is calculated by the same equation, manipulated to use the yaw rate of the lead vehicle AVz:

$$\text{USG\_Live} = \text{SteerESC/AVz/V} - \text{WB\_ESC/V}^2 \tag{3}$$

Equation 3 is applied only when AVz and V are non-zero.

> **Note** A good test for using USG_Live to determine a useful value for USG_ESC is a slowly increasing steer test (at constant speed), as done with ESC compliance tests such as FMVSS-126/ECE-R13H for passenger cars.

The average friction coefficient for all tires on the lead unit (Mu_ESC) is calculated and used to determine a maximum yaw rate (AVz_ESC_Max) as a limiting case when tire lateral forces are at the frictional limits. In this case, the total lateral force is μ•W, where W = mg, and the lateral acceleration is Ay:

$$m \bullet Ay = Fy = \mu \bullet m \bullet g$$

$$Ay = \mu \bullet g \tag{4}$$

Given that Ay = (yaw rate)•V, the maximum yaw rate is estimated as:

$$\text{AVz\_ESC\_Max} = \text{Mu\_ESC*G/V} \tag{5}$$

The yaw rate prediction (the output variable AVz_ESC_Pre) has the sign of the linear prediction, with a magnitude that is the smaller of the yaw rates calculated in Equations 2 and 5:

$$\text{AVz\_ESC\_Pre} = \text{sign(min(|AVz\_ESC\_Lin|, AVz\_ESC\_Max), AVz\_ESC\_Lin)} \tag{6}$$

The output variable Ay_ESC_Pre is the predicted lateral acceleration, calculated from the yaw rate by multiplying it with speed:

$$\text{Ay\_ESC\_Pre} = \text{AVz\_ESC\_Pre*V} \tag{7}$$

Risk of rollover

With heavy trucks, a major role of the ESC is to prevent lateral accelerations that can cause rollover. Three parameters define thresholds used to determine whether the ESC should activated to slow the vehicle: AY_LIMIT_ESC, AY_ROLL_LIMIT_ESC, and ROLL_LIMIT_ESC.

If the magnitude of the current lateral acceleration parallel to the road surface (Ay_Rd) is greater than the parameter AY_LIMIT_ESC, then all four brake pressure requests from the ESC are set to the parameter PBK_MAX_ESC.

If the current vehicle roll angle relative to the road surface (Roll_Rd) is greater than the parameter ROLL_LIMIT_ESC, and the magnitude of the predicted lateral acceleration Ay_ESC_Pre is greater than the parameter AY_ROLL_LIMIT_ESC, then all four brake pressure requests from the ESC are set to the parameter PBK_MAX_ESC.

In either of these cases — large lateral acceleration or large roll plus some predicted lateral acceleration —the output variable ESC_Active is set to one, and the throttle is set to zero.

Risk of loss of steering control

The predicted yaw rate AVz_ESC_Pre is compared to the actual yaw rate AVz to calculate a yaw-rate error, the output variable AVz_ESC_Err:

$$\text{AVz\_ESC\_Err} = \text{AVz} - \text{AVz\_ESC\_Pre} \tag{8}$$

An intervention brake delivery pressure is calculated when the error magnitude is greater than the yaw-rate dead-band parameter AVZ_DEAD_ESC:

$$\text{PdelAVz} = \text{KP\_AVZ\_ESC} * \max(|\text{AVz\_ESC\_Err}| - \text{AVZ\_DEAD\_ESC}, 0) \tag{9}$$

The delivery pressure PdelAVz is used to set one of the four ESC pressures, with the choice being determined by whether the yaw-rate error indicates too much yaw rate (oversteer) or not enough (understeer), and also by the direction of the intended steering (right or left). In oversteer conditions, the intervention braking is applied to the front; for understeer, it is applied to the rear.

For example, if the intended steering is to the left (positive steering and predicted yaw rate) and the error is positive (actual yaw rate is greater than predicted yaw rate), the vehicle is oversteering to the left and the intervention pressure is applied to the right-front wheel (PbkESC_R1). In all cases, the pressure is limited by the parameter PBK_MAX_ESC.

The four cases are:

If right turn, oversteer: PbkESC_L1 = min(PdelAVz, PBK_MAX_ESC)

If left turn, oversteer: PbkESC_R1 = min(PdelAVz, PBK_MAX_ESC)

If left turn, understeer: PbkESC_L2 = min(PdelAVz*R_Brake_ESC, PBK_MAX_ESC)

If right turn, understeer: PbkESC_R2 = min(PdelAVz*R_Brake_ESC, PBK_MAX_ESC) (10)

If the delivery pressure is greater than the parameter PBK_ACTIVE_ESC, then the output variable ESC_Active is set to one, and the throttle is set to zero.

Examples

CarSim: Sine with Dwell Tests

The ESC dataset shown earlier (Figure 2, page 3) is used for a Sine with Dwell sequence as specified in FMVSS 126 and ECE R13H. This procedure begins with two slowly increasing steer tests to establish reference steering wheel angles linked to a lateral acceleration of 0.3g.

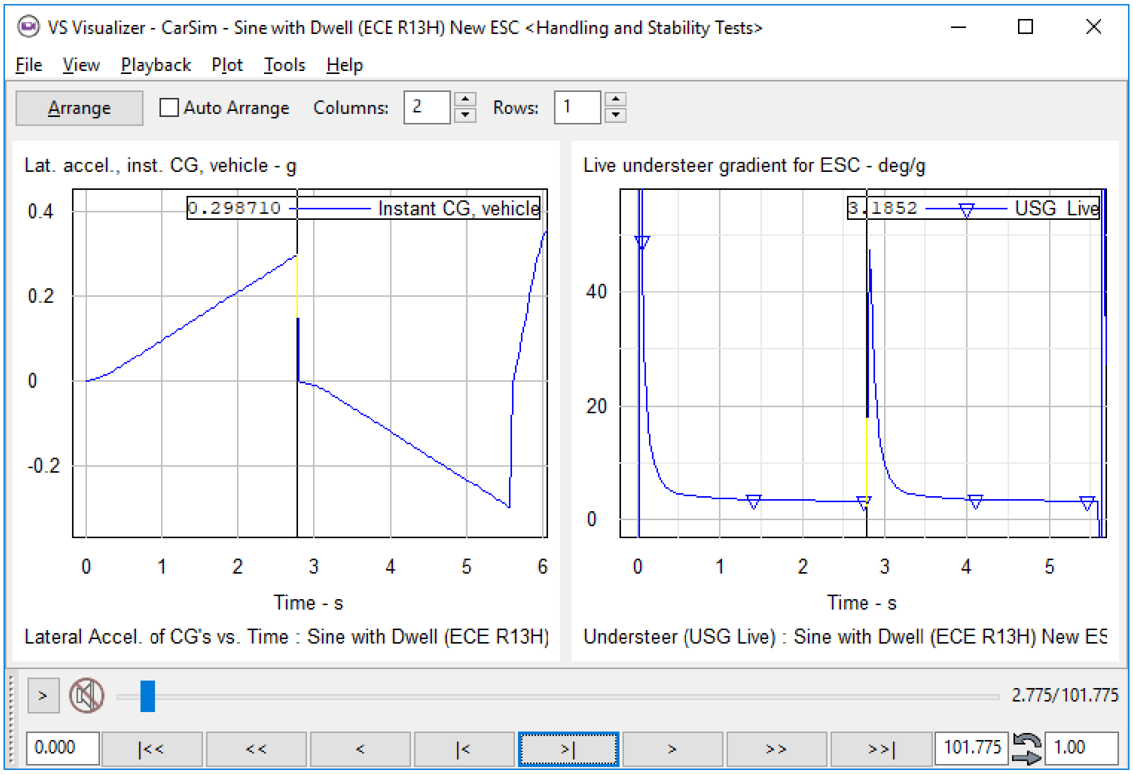

Figure 4. Time history plots of lateral acceleration and USG_Live for slowly increasing steer.

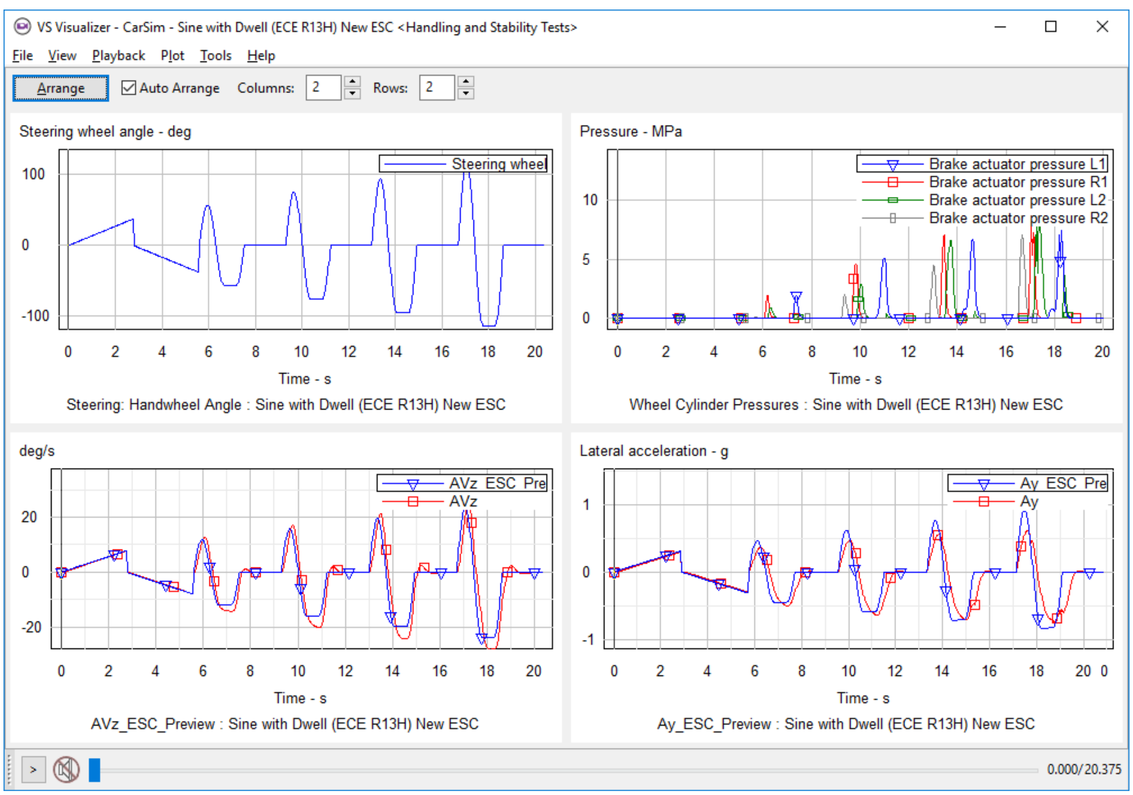

Figure 5. Some of the early cycles in the sine with dwell series.

Figure 4 shows two plots involving the slowly increasing steer: lateral acceleration, and understeer gradient calculated according to Equation 3. When the lateral acceleration almost reaches the limit of 0.3g, the `USG_Live` variable has a value of 3.19, which is the value specified for the ESC parameter in the example dataset.

Figure 5 shows four more plots covering the slowly increasing steer tests (up to 5.5s), followed by several Sine with Dwell tests. These show the steering that is provided by a steering robot used in physical testing, yaw rate and lateral acceleration (both actual and predicted by the simple ESC model), and the resulting braking interventions.

> **Note** The ESC examples in TruckSim have the vehicle performing a step-steer maneuver.

Do More: Extend the Example

This example presents a very simple concept of an ESC. You can extend it to make it more realistic and versatile. These are just a few suggestions among many.

1. Allow for the integration with another controller that is implemented in external code (e.g., Simulink). To do it, use intermediate variables from the ESC and from the Simulink import, then put the sum of the effects of the two controls into the import variables.
2. Use a more detailed representation of the vehicle handling capability than understeer gradient, such as a lookup table of the yaw velocity gain as a function of lateral acceleration and speed.
3. Extend the controller to apply brakes to trailers in yaw control and rollover control events.
4. Incorporate an anti-sway control for the trailer.