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PBS Safety Standard Testing Using TruckSim

Introduction

Performance Based Standards (PBS) have been proposed as a scheme for regulating truck configurations acceptable on national highway systems in a number of countries, with the main development taking place in Australia.

Road networks in Australia are classified in four levels: level 1 is the entire system, including dense urban environments; level 2 covers the main arterial roads throughout the country; level 3 covers more isolated roads with less of a range of grades and curves as well as less traffic; and level 4 covers isolated roads over long distances with minimum traffic. The PBS Scheme certifies vehicles for use in these four levels of road networks.

The reference document for the PBS Scheme is *Performance Based Standards Scheme — The Standards and Vehicle Assessment Rules*, published in November 2008 by the Australian National Transport Commission (NTC). The NTC document includes *Appendix C: The Safety Standards*, which defines a number of safety standards that are used by designated PBS Assessors and Certifiers to verify that new vehicle configurations meet PBS requirements.

Determining whether a truck configuration meets a specific safety standard can be determined by in-vehicle testing or by numerical analysis, as described in *Appendix E: Assessing Safety Standards by Numerical Modeling*.

This memo describes how simulation of the PBS safety tests is done with the TruckSim software. Table 1 lists the safety standards covered in this memo, along with the associated test procedures. In some cases, the same test procedure is used for multiple standards. For example, Safety Standards C7-C10 all involve data that can be taken from a single simulated test.

Table 1. PBS Appendix C Safety Standards (Nov. 2008).

Title	**Test Procedure**	**TruckSim Vehicle Data**
C1. Startability	Start from zero speed on grade	Powertrain, dimensions, masses, suspensions, aerodynamic drag, tires
C2. Gradeability	Maintain motion and speed	
C3. Acceleration Capability	Accelerate from zero speed	
C5. Tracking (Straight)	Drive at speed on rough road with cross-slope	Dimensions, masses, inertias, suspensions, tires
C7. Low-Speed Swept Path	90° turn, 12.5-m radius	Dimensions, masses, suspensions, steering, tires
C8. Frontal Swing		
C9. Tail Swing		
C10. Steer-Tire Friction		
C11. Static Rollover	Tilt Table test	Dimensions, masses, suspensions, tires
C12. Rearward Amplification	Lane change	Dimensions, masses, inertias, suspensions, steering, tires
C13. High-Speed Tracking		
C14. Yaw Damping Coefficient	Pulse steer	
C15: Handling Quality	Not yet defined	
C16: Stability Under Braking	Brake Test	Dimensions, masses, suspensions, steering, tires, brakes

The table also gives a rough overview of the critical vehicle data. If all of the procedures were simulated, then the same TruckSim vehicle dataset would be used for the vehicle in all cases and would include all components supported in TruckSim. On the other hand, if standards C1-C3 were done by means other than TruckSim, then a detailed powertrain dataset would not be needed in the TruckSim model to perform the remaining PBS tests.

Running in TruckSim

Each PBS test listed in Table 1 (other than C15) is provided as one or more **Procedure** datasets in TruckSim. Further, one run has been made for each test that can be used as an example to view and copy.

> **Note** Running PBS tests in TruckSim requires familiarity with both the PBS standards and the TruckSim software. At a minimum, you should have completed the TruckSim *Quick Start Guide* and have gone through the example runs in TruckSim. You should also be familiar with Appendix C and Appendix E in the NTC PBS reference document.

Although all of the tests can be run for any TruckSim vehicle dataset, evaluation of some of the simulation results involves plots of paths of points of interest. For these tests, it is necessary to specify valid coordinates for points that are referenced in the PBS Safety tests.

Reference Points and Motion Sensors Used for Tracking Evaluation

TruckSim supports up to 99 Motion Sensors for the vehicle being simulated. Datasets for the Motion Sensors, which can be used to calculate the trajectories of the points, are contained in the library submenu **Positions, Velocities, and Accelerations**, from the **Libraries** menu **Custom Forces and Sensors** (Figure 1). Coordinates should be set according to the locations shown in Table 2. Points 1 and 6 are the front corners of the body; points 5 and 10 are the rear points, and the others are on the left and right edges.

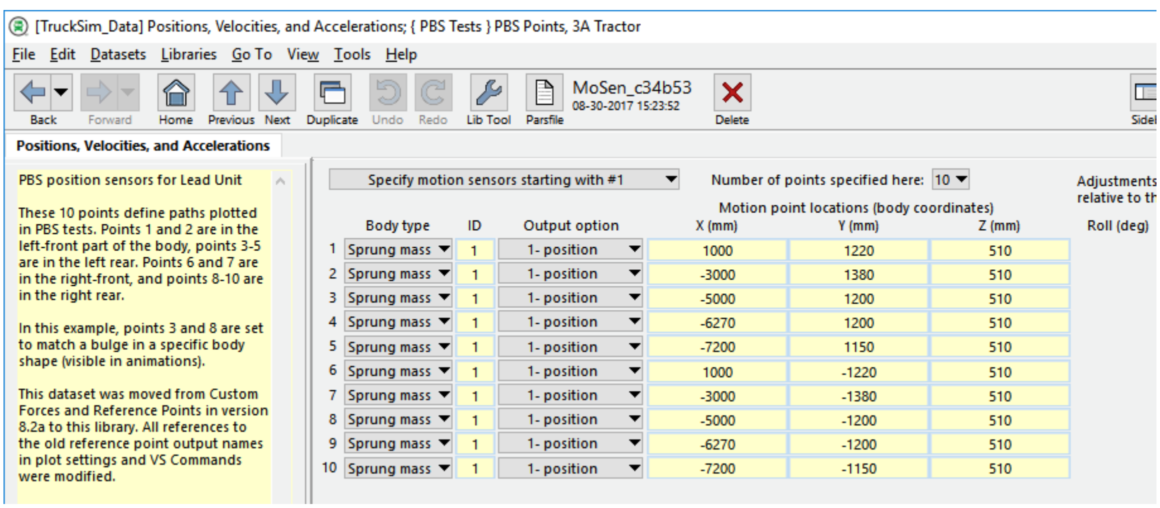


Figure 1. Screen for setting coordinates of ten Motion Sensors for a sprung mass.

Table 2. Motion Sensors in each sprung mass.

Point	Location
1	Left-front corner
2	Optional point of interest on left side
3, 4	Left side near axle or suspension
5	Left-rear corner
6	Right-front corner
7	Optional point of interest on right side
8, 9	Right side near axle or suspension
10	Right-rear corner

The existence of motion sensors does not directly affect the vehicle behavior, and therefore, TruckSim vehicle datasets typically do not have these points specified. When used for the PBS Scheme, datasets for the Motion Sensors should be created and linked to the vehicle description. This can be done from either the **Vehicle: Loaded Combination** screen or an individual Vehicle Unit screen (lead unit or trailer), or a **Vehicle: Sprung Mass** screen.

Figure 2 shows an example dataset for a tractor-semitrailer combination with links to Motion Sensors for the lead unit 1 and trailer 2.

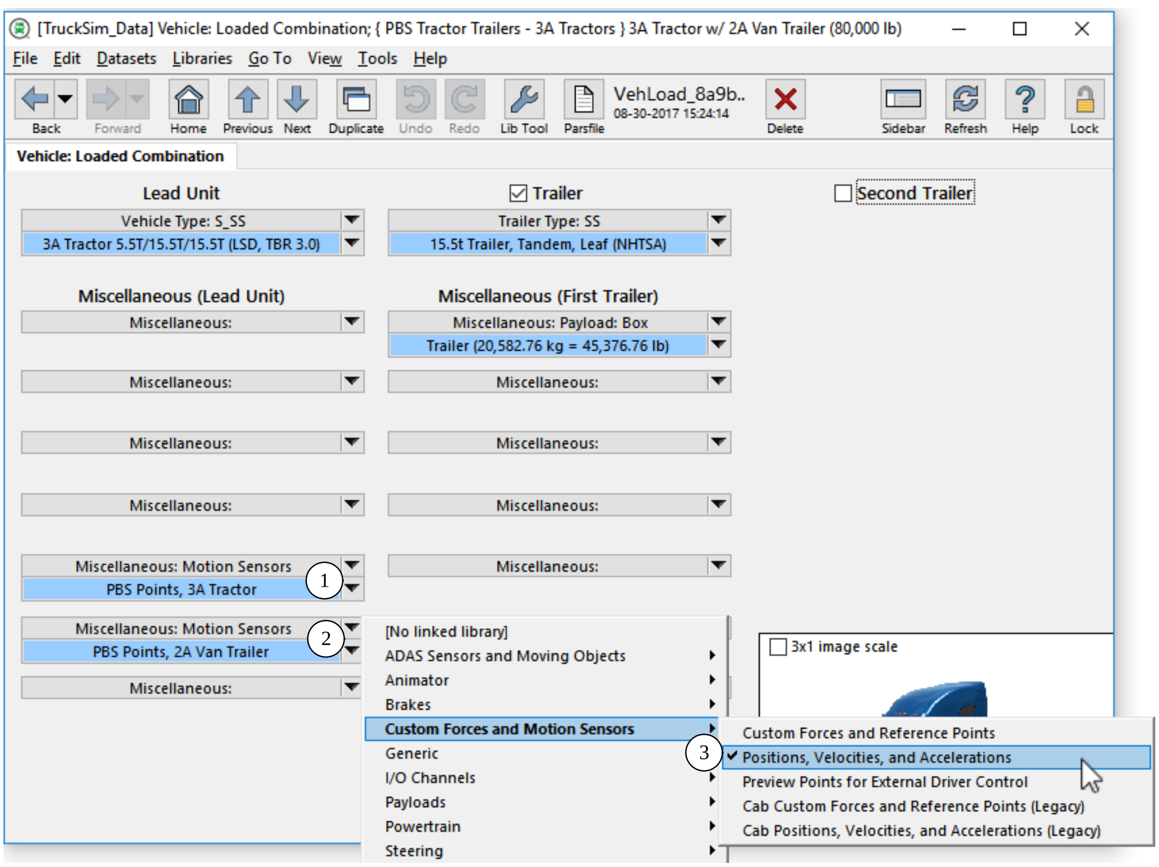


Figure 2. Linking sets of Motion Sensors to a vehicle loaded combination dataset.

Running a PBS Test

The method for applying an existing test in TruckSim to a new vehicle is typically as follows:

1. From the **Run Control** screen, use the **Datasets** menu to navigate to the example run for the test of interest. It will have the correct **Procedures** link and plot dataset links.
2. Make a new **Run Control** dataset by clicking the **Duplicate** button or typing Ctrl+N.
3. Change the link from the example vehicle to a new vehicle of interest. This is typically a dataset from the **Vehicle: Loaded Combination** library that has the vehicle, payloads, and links to the PBS Motion Sensors (Figure 1, Table 2, Figure 2).
4. Select other links on the **Run Control** screen (i.e., other than the vehicle and procedure) and adjust as necessary to match the type of vehicle or a variation of the procedure.
5. Click the button **Run Math Model**.
6. Click the **Plot**, **Video,** or **Video + Plot** buttons to view the simulation results.

Evaluating the Results

Results from TruckSim should generally be treated the same way as in-vehicle measured test data when evaluating the success or failure of the vehicle in the test. In most cases, you will inspect plots generated from the simulation results to evaluate the success or failure of the vehicle in the simulated test. Animations should be viewed to confirm that a test proceeded as intended, and in some cases, to help diagnose why the results aren't as expected.

TruckSim automatically sets up the initial conditions of the vehicle on the road to be in approximate equilibrium. However, some adjustments often occur in the first few simulated seconds. Most of the PBS simulations include a few seconds of simulation before results are written to file, such that the vehicle is in a realistic condition from the start of the recorded data.

Some of the standards specify performance levels that can be obtained directly from plots of TruckSim variables. For example, speeds, global coordinates of axle centers, and global coordinates of reference points can be accessed from VS Visualizer. Other measures are not directly calculated but can be obtained by measuring scaled plots or by using external software. For example, swept path measures are obtained by comparing trajectories of different points on the vehicle. The measurements taken between paths cannot be obtained directly from the TruckSim math models at an instant of time because the points of interest were recorded at different times. For example, points from the back of the vehicle reach the locations of interest much later than points in the front of the vehicle.

The primary objective of the example procedures is to replicate the tests. You may have to use post-processing methods or hand calculations to evaluate results for some of the standards, just as you would with in-vehicle measured test results.

Powertrain: Startability, Gradeability, and Acceleration

The first three standards are intended to minimize safety risks by ensuring that vehicles have the necessary capabilities to maintain speeds and will not interfere with other vehicles on the road.

Performance is evaluated by the capability of the vehicle to travel at given speeds or accelerations on specified grades.

Model Requirements

Any vehicle in TruckSim that makes use of the detailed powertrain model can be run with PBS tests C1, C2, and C3. Along with the physical properties of the mechanical powertrain parts, shifting behavior (e.g., upshift and downshift tables) will be used.

Aerodynamic drag should be specified when it affects the sustainable speed required in C2 (at least 60 km/h for level 4, and up to 80 m/h for level 1). On the other hand, aerodynamic effects related to aerodynamic slip can usually be neglected because the vehicle does not turn in C2.

Details of the brake and steering systems are not critical for these tests. Suspension spring rates and load sharing are important; however, the kinematic and compliance effects related to steering are not as influential since these are straight-line tests.

The tire model is needed to predict load vs. deflection and longitudinal force. However, the tire data involving lateral effects are not as influential since the slip angles are typically very small.

The procedure dataset for this test is valid for vehicles with either automatic or manual transmissions. It specifies closed-loop control for manual transmissions with a clutch. If the vehicle has an automatic transmission (torque converter) the control settings for the clutch are ignored.

Startability (C1)

This standard is intended to ensure that a vehicle has adequate starting capability on a grade. Depending on the road class on which the vehicle is operating the test grades range from 5% to 15%. From a standing start on the grade the PBS vehicle must start and maintain steady forward motion. Figure 3 shows an example **Run Control** dataset for this test.

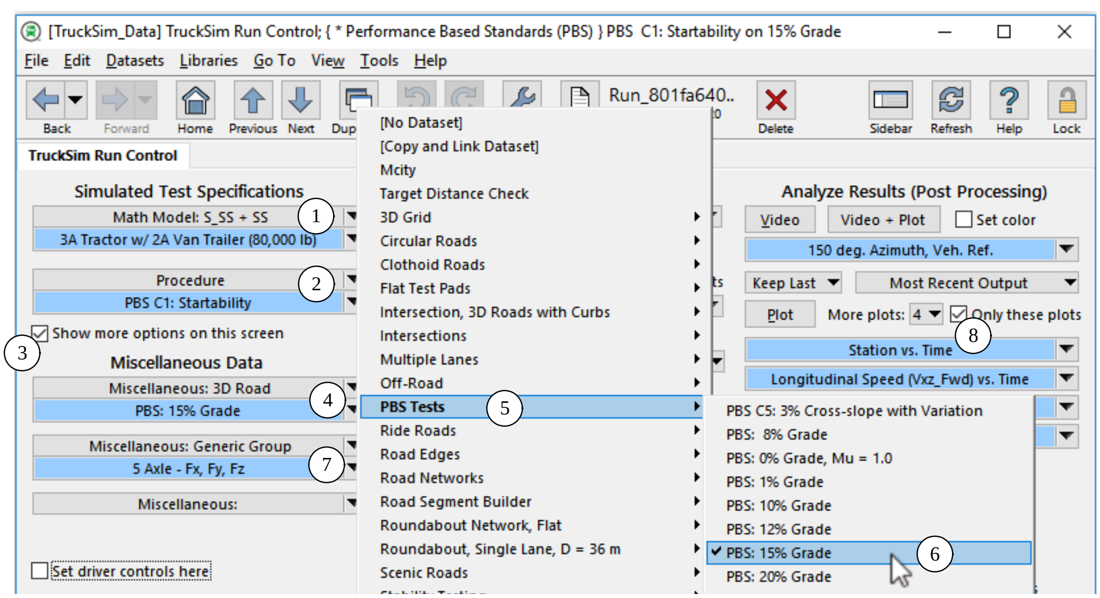


Figure 3. Setup for C1: Startability Test.

Setting Up the Run

Three links are needed on the TruckSim **Run Control** screen to set up the run.

Vehicle: Link to a dataset for the vehicle of interest in the fully loaded condition (1).

Procedure: Link to the **Procedures** dataset **PBS (Performance Based Standards)>PBS C1: Startability** (2).

More: Check the box **Show more options on this screen** (3). Use one of the miscellaneous links to select a road dataset (4) from the road library (**Paths, Roads, and Ground>Road: 3D Surface)**. The road dataset should be from the submenu **PBS Tests** (5), and have the grade of interest for the PBS Class level (5%, 10%, 12%, or 15%).

In the example, another link is used to show arrows indicating tire forces in animations of the test. A miscellaneous link (7) is used to specify a dataset in the **Generic Data Group** library with animation information for tire force arrows for the number of axles on the lead unit or possibly the entire vehicle.

Evaluating the Results

If the vehicle travels forward 5m, then the vehicle passes this test. If not, the reason for the failure can be determined by viewing the animation and plots.

Performance in this test is limited by the ability of the vehicle to develop adequate tractive force at the drive wheels on startup. Failure of this test could be due to insufficient powertrain torque on the drive wheels or insufficient friction on one or more of the drive tires.

If you uncheck the box (8) to show only the plots specified on the Run Control screen, then the plots selected on the **Procedures** screen (2) will be shown. This may give more insight into the vehicle behavior during the simulation.

Gradeability — C2(A): Maintain Motion

The C2 Gradeability standard defines two tests. The first, C2(A), tests the capability of the vehicle to maintain motion, even if very low speed is necessary, on a steep grade ranging from 8% to 20%. The test setup in TruckSim is almost the same as used for the C1 Test (Figure 3).

Setting Up the Run

Three links are needed on the TruckSim **Run Control** screen to set up the run.

Vehicle: Link to a dataset for the vehicle of interest in the fully loaded condition.

Procedure: Link to the **Procedures** dataset **PBS (Performance Based Standards)>PBS C2(A): Gradeability (Maintain Motion)**.

More: Check the box **Show more options on this screen** (under the **Procedure** link). Use one of the miscellaneous links to select a road dataset. First, link to the road library (**Paths, Roads, and Ground>Road: 3D Surface)**, and then link to one of the grades specified for the C2(A) test (8%, 12%, 15%, or 20%).

Evaluating the Results

The vehicle passes this test if the vehicle maintains forward motion and has reached either a steady speed or a steady cycle, as indicated by the plot of speed vs. time.

If the vehicle slows and reaches a negative speed, then it has failed for the selected grade and initial speed. You can go to the **Procedures** dataset and change the initial speed. Also, you can view more plots related to the procedure to diagnose why the vehicle lost speed.

The PBS scheme specifies four grade levels. If it is not possible to maintain speed on the high grade, then change to a road with less grade and try again.

Gradeability — C2(B): Maintain Speed

The second Gradeability test, C2(B), determines the capability of a vehicle to maintain a specified minimum speed on a 1% grade. The test setup in TruckSim is almost the same as used for the C1 Test (Figure 3).

> **Note** The minimum required speed varies depending on the PBS road class. Please see Appendix C of the NTC document for details.

Setting Up the Run

Two links are needed on the TruckSim **Run Control** screen to set up the run.

Vehicle: Link to a dataset for the vehicle of interest in the fully loaded condition. Other than the loading conditions, no special properties are needed to run this test.

Procedure: Link to the **Procedures** dataset **PBS (Performance Based Standards)>PBS C2(B): Gradeability (Maintain Speed)**. This dataset includes a link to the road surface with a 1% grade.

Evaluating the Results

The procedure sets up a target speed of 81 km/h that is used to set the initial conditions of the vehicle, as well as a target for the built-in TruckSim closed-loop speed controller.

If the vehicle maintains the specified minimum speed for the PBS road class, then it has passed the test. If it slows below the minimum specified speed for the PBS road class, then the vehicle has failed the test.

According to NTC PBS Appendix C, the minimum sustained steady speed must be measured and recorded as the achieved performance value, rounded down to the nearest whole number. If the speed is still slowing at the end of the run, you can increase the run time (on the **Procedures** dataset), or select a lower speed. After changing the settings, repeat the run to see if the lower level was achieved.

Acceleration Capability (C3)

The purpose of this standard is to minimize safety risk associated with travel through intersections and rail crossings by specifying minimum times for a PBS vehicle to accelerate from rest, to increase speed, and travel 100m within a specified time on a road with no grade.

Setting Up the Run

Two links are needed on the TruckSim **Run Control** screen to set up the run.

Vehicle: Link to a dataset for the vehicle of interest in the fully loaded condition.

Procedure: Link to the **Procedures** dataset **PBS (Performance Based Standards)>PBS C3: Acceleration Capability**.

Evaluating the Results

The plots of vehicle distance and target distances indicate the PBS level achieved in the simulation (Figure 4). If the line for the vehicle position is above the line for a PBS level (see the first plot in Figure 4, then the vehicle is OK for that level.

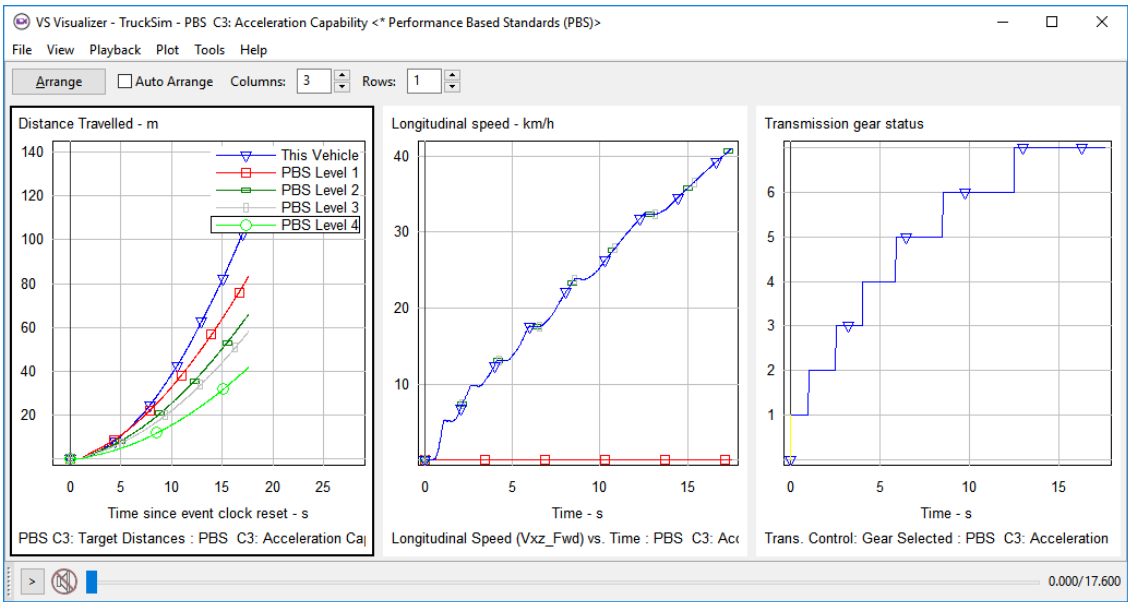


Figure 4. Results from PBS C3: Acceleration Capability.

Tracking Ability on a Straight Path (C5)

The purpose of this standard is to minimize safety risk associated with lane width and lateral clearance by ensuring that a PBS vehicle remains within its traffic lane when traveling at high speed on straight roads with uneven surfaces. The main component of this procedure is a road with properties specified in C5: it has an average crossfall (cross-slope) of 3%, a standard deviation crossfall of at least 1%, and each travelled wheeltrack has an International Roughness Index (IRI) roughness of at least 3.8 m/km. The purpose of the test is to see how much the vehicle trailer(s) drift to the side when the driver steers such that the front axle follows a more or less straight line.

Model Requirements

This test makes use of most features of a TruckSim vehicle model. However, given that the test uses a constant target speed, the brake system is not used, and the detailed powertrain model and aerodynamic drag do not heavily influence the vehicle's performance.

The suspension models predict kinematical interactions of steering and roll with deflection, and the tire models predict the resulting forces and moments that affect axle tracking. Given that the vehicle is travelling in a nearly straight line, limit effects (high slip, large ranges in load, etc.) are not expected in this test.

Tracking of the simulated vehicle involves plotting the X and Y coordinates of the front and rear Motion Sensors on each side of each sprung mass unit (Table 2, page 4).

Setting Up the Run

Two links are needed on the TruckSim **Run Control** screen to set up the run.

Vehicle: Link to a dataset for the vehicle of interest in the fully loaded condition, with links to Motion Sensors for each vehicle unit.

Procedure: Link to the **Procedures** dataset **PBS (Performance Based Standards)>PBS C5: Tracking on a Straight Path**.

Evaluating the Results

The plots of Y vs. X coordinates of the reference points show the tracking behavior (Figure 5). When viewing the plots, you can read values for the current location of the cursor. (If the values are not shown, click in the plot area and press the ‘V’ key.) Switch between plots using the tab key, and use the up/down arrow to find the max or min values. For example, the maximum Y coordinate on the left side is for the rear of Unit 2, with a value of 1.49051 m.

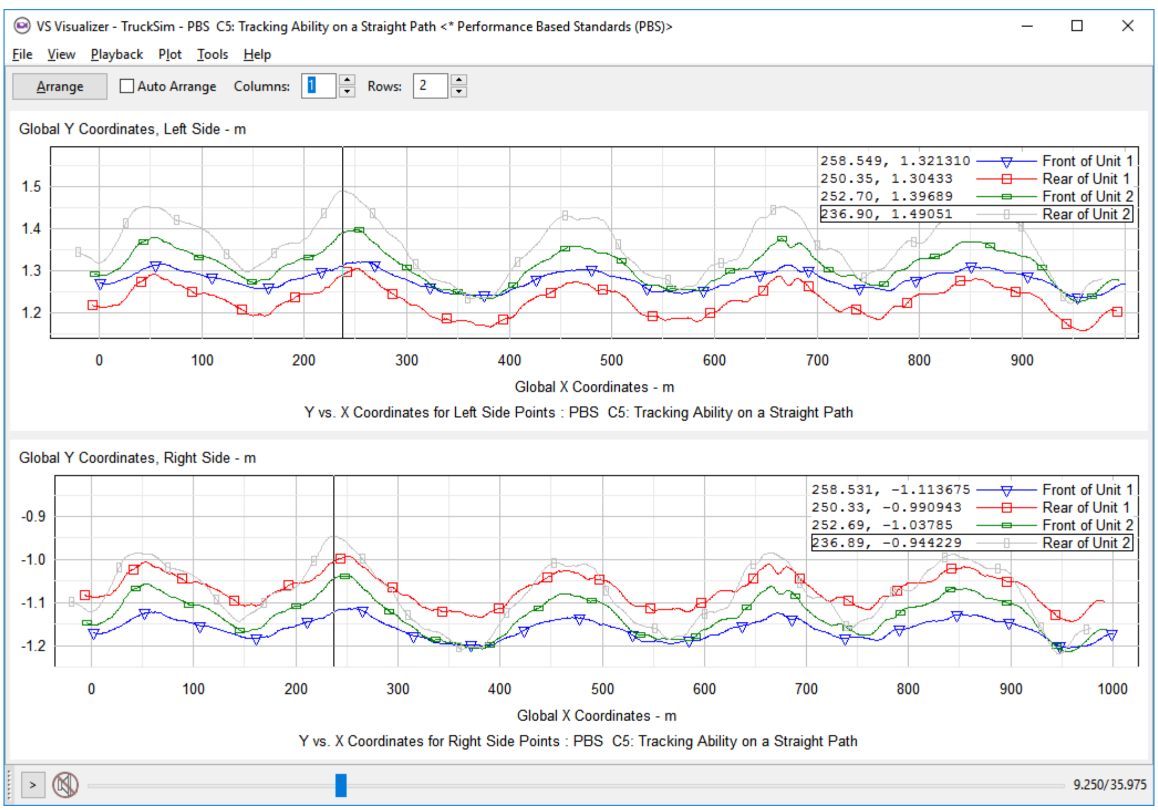


Figure 5. Tracking of points of interest on a laterally inclined road surface.

Low-Speed 90° Turn (C7, C8, C9, C10)

A 90° turn with a radius of 12.5 m is used to evaluate tracking and friction utilization for low-speed turning. Three of the standards concern the space required by the PBS vehicle when turning at an intersection, and another concerns the friction utilized by the front tires. All four standards can be applied with just two simulations: one for a left turn and one for a right turn.

The test has the vehicle travelling in a straight line, then turning such that a reference point on the outside sidewall of the outside front tire (Figure 6) follows a 12.5m radius turn for 90°, then exits, following a straight line perpendicular to the entry line. For example, Figure 7 shows tire paths for a tractor-semitrailer combination vehicle making a left-hand turn.

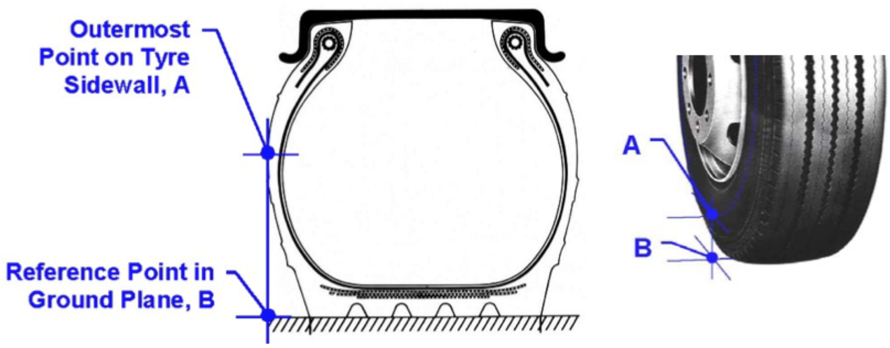


Figure 6. Outside wheel reference point (Figure 7, p. 38, NTC PBS, Nov. 2008).

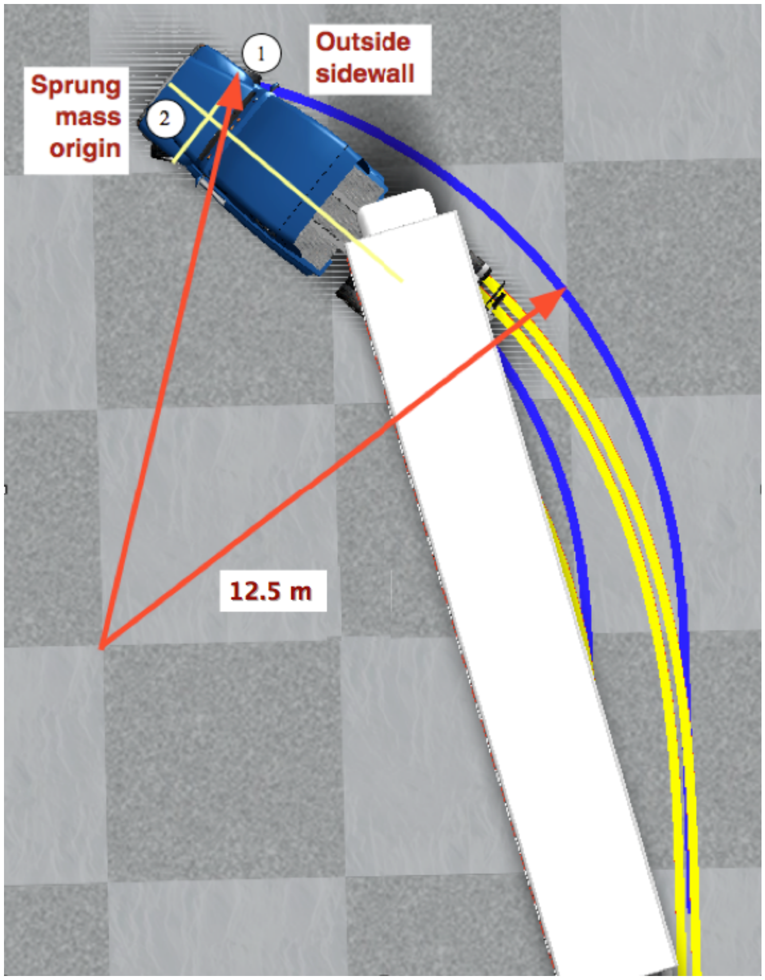


Figure 7. Tracking during a 12.5-m radius turn.

Model Requirements

This test runs at a constant low speed. Some aspects of the vehicle model have little to no effect on the vehicle behavior, including the brake system, aerodynamics, and the inertia properties. On the other hand, nonlinear tire properties can be significant, along with the steering system and steering effects of the suspensions. Powertrain details – engine torque curve; manual or automatic transmission; transmission gear ratios; differential and transfer case properties; number and location of driven axles – all influence the test results.

Tracking of the simulated vehicle involves plotting the X and Y coordinates of the front and rear Motion Sensors on each side of each sprung mass unit (Table 2, page 4), along with other Motion Sensors representing axle locations.

The test procedure provided in the TruckSim Low-Speed Swept Path test sets the vehicle speed to 5 km/h. The ground is flat with a friction coefficient of 1.0, and a target path is defined for the 12.5m radius turn. The PBS test requires the driver to have the tire reference point (Figure 6) follow the target path with lateral tracking error less than 50 mm.

Setting Up the Run

Figure 8 shows the **Run Control** screen for a low-speed turn using the 12.5m radius path. As with other tests, the first two links are to the vehicle being simulated (1) and the procedure (2). There are two options for the basic procedure: a turn to the left and a turn to the right.

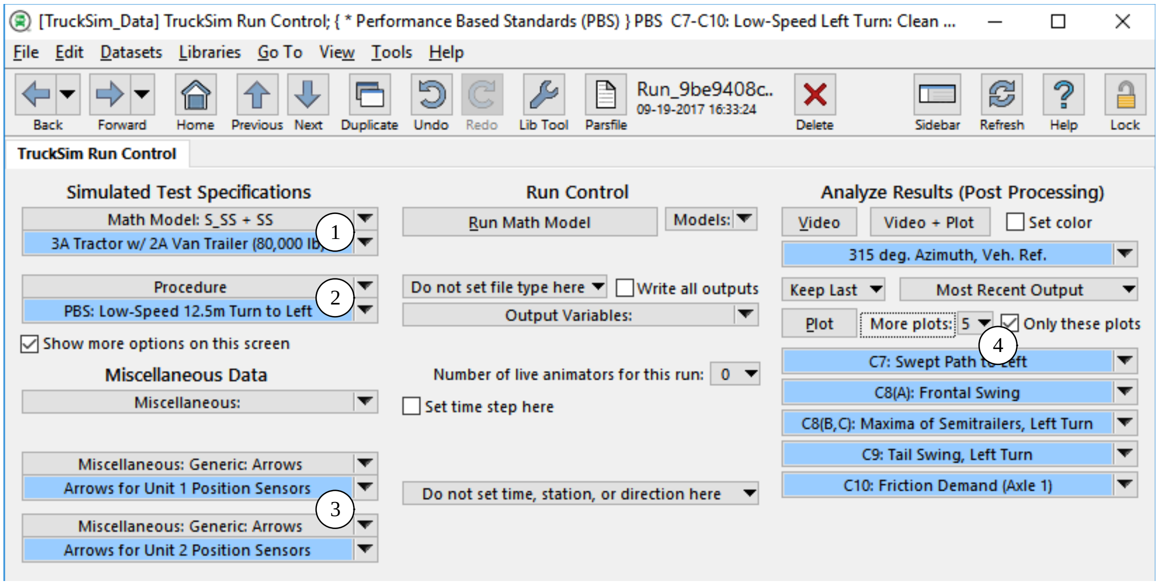


Figure 8. Example run with low-speed turn for C7-C10 standards.

The **Run Control** screen for the Low Speed Turn test also includes **Generic Data Group** links (3) to visualize where and how each of the Motion Sensor locations are tracking through the test.

As noted earlier, a single run provides the data needed to evaluate the vehicle for four PBS standards: C7, C8, C9, and C10. Evaluation is made by inspecting plots (4).

Figure 9 shows the **Procedures** dataset for the low-speed turn to the left.

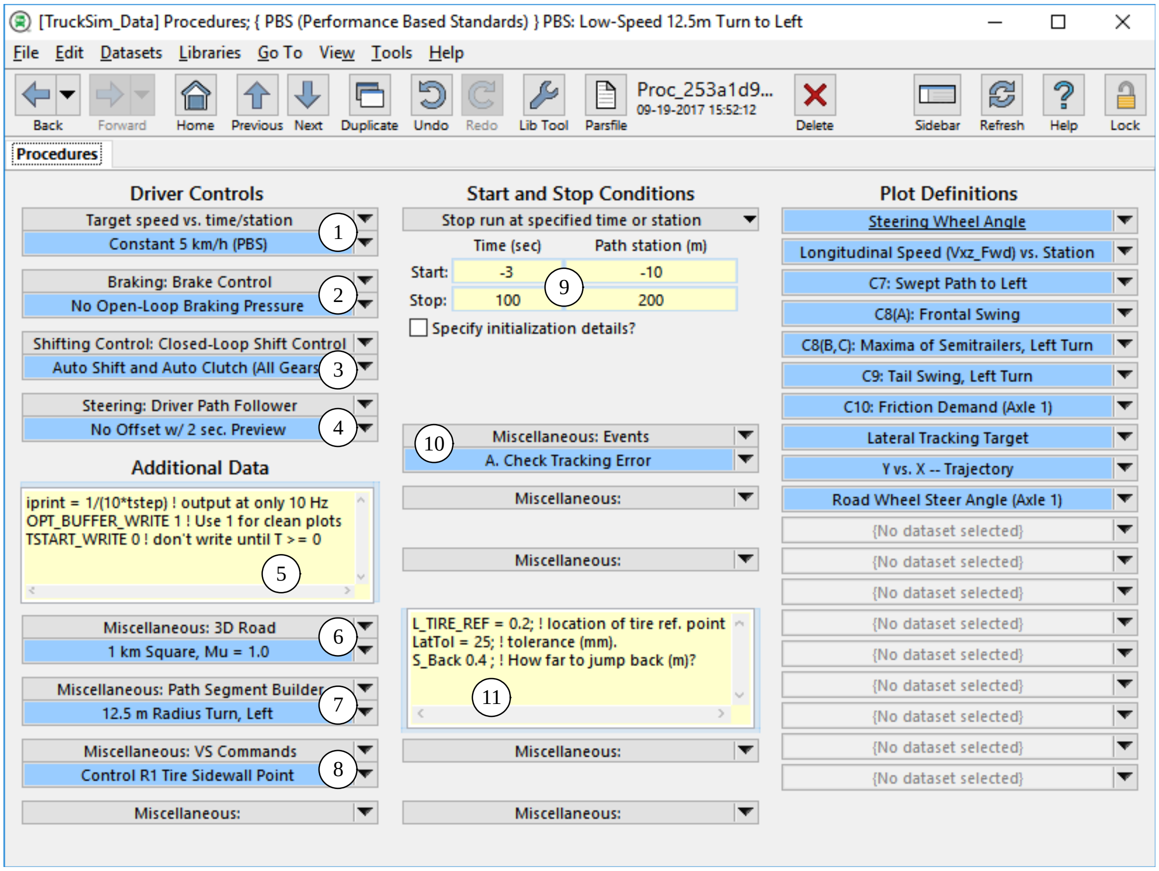


Figure 9. Procedure dataset for low-speed PBS turn.

The driver controls are set as might be expected for this type of low-speed maneuver: the speed controller is set to run at 5 km/h (1); open-loop braking is disabled (2); shifting control is closed-loop (3) (this might need to be adjusted for some vehicles; manual gear selection is an option if the proper gear is known); and the closed-loop steer controller is set to follow a path (4). The ground is specified with a flat and level road surface with a friction coefficient of 1.0 (6). The target path is a 90° turn with a 12.5m radius (7). Datasets representing the paths are included in the database: one to the left and one to the right.

The advanced parts of this procedure are contained in a set of VS Commands that add variables to the model (8), and a short sequence of VS Events that also add variables (10).

Some advanced settings are made in the two miscellaneous yellow fields. The first miscellaneous yellow field (5) has three lines involving the way outputs are written to file. Because this is a low-speed test involving a long simulation time (9), the output time step is set to about 0.1 sec, keeping the size of the output file reasonable as well as speeding up post-processing. This is done by setting the system parameter `IPRINT = 1 /(10*TSTEP)` (5).

The vehicle might not be in full static equilibrium when the run starts, so the initial time is set to a negative value (10) and a system parameter `TSTART_WRITE` is set such that writing to the output file will not start until the simulation time reaches zero (5).

Advanced Control Method

The built-in closed-loop steering controller previews the target path specified for the origin of the lead unit's sprung mass. This origin is typically located at a point in the sprung mass that nominally coincides with the center of the front axle (2) (Figure 7, page 12). The controller uses a reference path (in this case, the 12.5m turn) along with a lateral offset. The lateral offset is initially the distance in the Y direction of the vehicle between the origin of the sprung mass coordinate system and the outside of the outside front tire (1). However, the vehicle is not necessarily tangent to the curve during the turn, so the lateral offset changes between the 12.5m radius path and the sprung mass origin. Therefore, VS Commands are used to adjust the lateral offset to keep the tire reference point within a specified tolerance of the path.

The control method used for this test is advanced. If the lateral offset of the tire reference point (on the outside sidewall, Figure 6) reaches a tolerance, then the math model changes the target position for the origin of the sprung mass, backs up in time, and tries again. Two options exist for writing to file, based on the system parameter `OPT_BUFFER_WRITE`. If set to 0 (the default in TruckSim), it writes to file based on the output time step (0.1 in this case). If the model backs up in time, then the file shows both the original and the repeat versions. On the other hand, if `OPT_BUFFER_WRITE` is set to a non-zero value (i.e., 1, (5)), then outputs are saved in memory and not written until the run ends. In this case, only the "final" results are shown.

For normal use, `OPT_BUFFER_WRITE` is set to 1 to provide clean plots and animations that show the vehicle motions for the test. If set to 0, the output files contain the iterations used to generate the steering needed to follow the target path. Note that showing all of the iterations in the plots and animations can be useful to better understand how the TruckSim simulation is proceeding and gain insight into what is required to successfully complete the test.

Three parameters defined for this test are shown in the second Misc. yellow field (11). `L_TIRE_REF` is the lateral distance from the center of the tire to the outside sidewall. This is a positive number that should be set in meters (e.g., 0.2). `LatTol` is the tolerance for the controller, in mm. The PBS standard requires that tracking be within a total of 50 mm (i.e., +/- 25 mm). This value can be changed here to try to get tighter tracking. As noted above, if the tracking limit is reached, the math model changes the target and backs up in time to try again. The parameter `S_Back` specifies how far the vehicle backs up, in meters. (The time is `S_Back/Vx`, where `Vx` is the forward speed in m/s.)

Note A detailed flow chart of this test sequence, along with a list of selected VS Commands and TruckSim variables, are included at the end of this Tech Memo. See Appendix A: Control Strategy Flow Chart for Low Speed Turn test and Appendix B: Index of Selected VS Commands and TruckSim Variables.

Low-Speed Swept Path (C7)

The purpose of this standard is to minimize the safety risk associated with turns at intersections by limiting the road space required by a PBS vehicle when making low-speed turns. The swept path is the maximum distance between the outermost and innermost trajectories of points on the vehicle. The swept path plot for a left-hand turn shows the paths of the tire sidewall point, Motion

Sensor 6 in the lead unit (unit 1), and Motion Sensors 3 and 4 in the trailer (unit 2). Figure 10 shows the trajectories for a vehicle with two units making a left-hand turn. Notice that the point on the sidewall of the right-front tire is shown in the video with a green sphere, and that red arrows show points of interest in the lead unit.

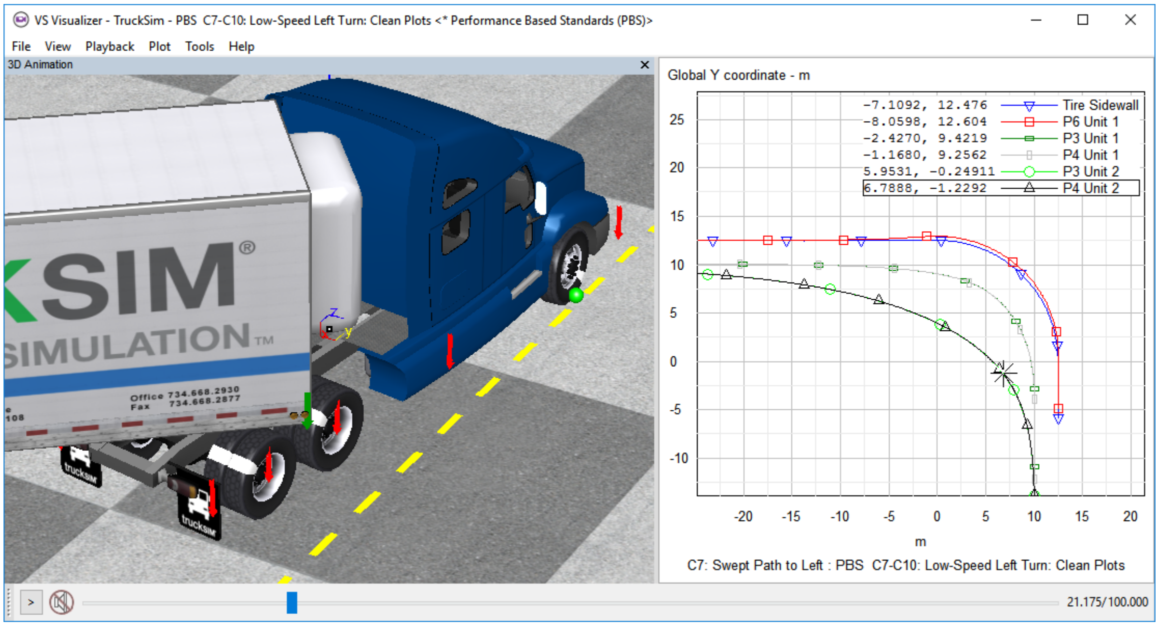


Figure 10. Plot of points used to determine swept path.

Details for measuring the swept path are provided in Appendix C of the NTC PBS document.

Frontal Swing (C8)

Frontal swing is a measure of the additional space needed by a PBS vehicle in a tight turn due to the overhang at the front of the lead unit (Figure 11).

Part A: Lead Unit (Rigid Trucks, Prime Movers, Buses and Coaches)

The C8(A) Plot (Figure 12) shows the lateral position of either point 1 (right-hand turn) or point 6 (left-hand turn) along with the reference point (tire sidewall) as a function of station (distance along reference path). The lateral tracking is defined to be perpendicular to the target path. In this case, the maximum value is found using the Ctrl+Up key in VS Visualizer (0.448 m).

Parts B and C: Semi-Trailers

The tracking of the outside front corners of all units are evaluated at the end of the turn to determine the maximum of the differences in outboard position (part B) and the difference of the maxima (part C). As set up in TruckSim, the start of the maneuver has the vehicle running parallel with the global Y axis and turning left or right, finishing with the reference point at the outer front tire at a global coordinate of Y = 12.5 m. Any Y coordinate values higher than 12.5 m represent an overshoot of the path.

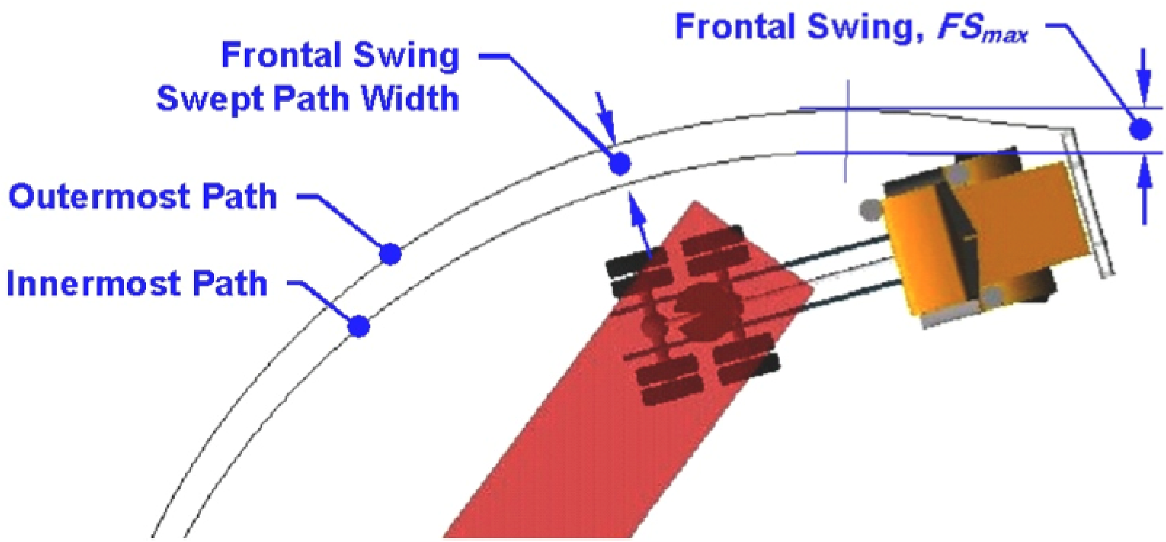


Figure 11. Frontal Swing (Figure 8, p. 40, NTC PBS, Nov. 2008).

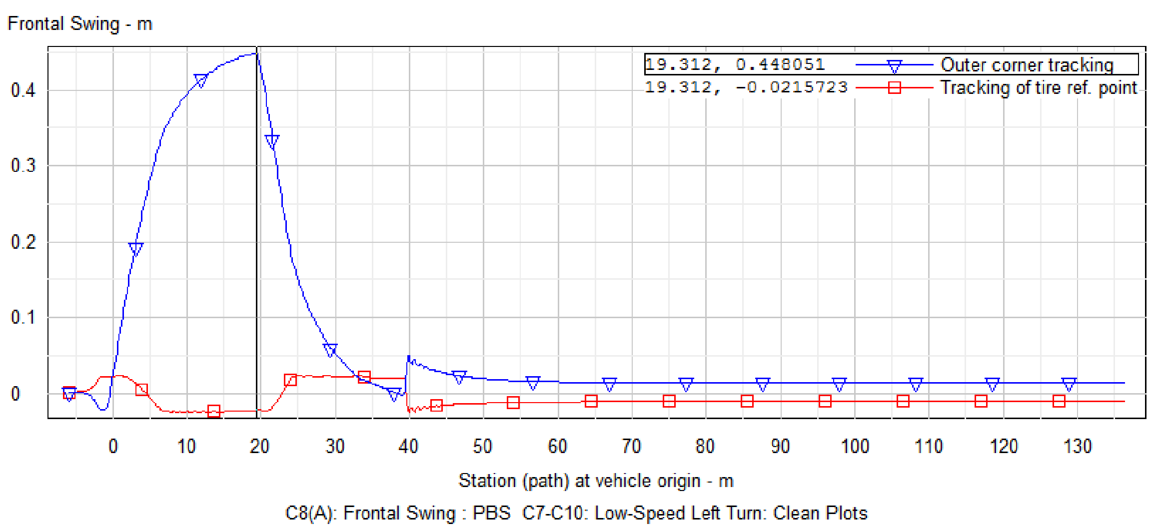


Figure 12. Plot of tracking of outer corner and reference point.

The C8(B and C) Plot (Figure 13) shows the Y coordinates of the reference tire point with the outside front corner points of all units in the vehicle. In this case, the maximum value occurs for unit 1, with a value of 12.948m (an overshoot of 0.448m relative to the 12.5m reference).

Tail Swing (C9)

Tail swing is considered by the rear outside points at the start of the turn. Given that the vehicle is initially travelling parallel to the global Y axis, tail swing is evaluated by looking at the X coordinates of the rear outside corners of all units on the vehicle (Figure 14). In this example, the maximum X coordinate for the trailer corner is at the start of the turn (12.505m), and is due solely to the width of the trailer.

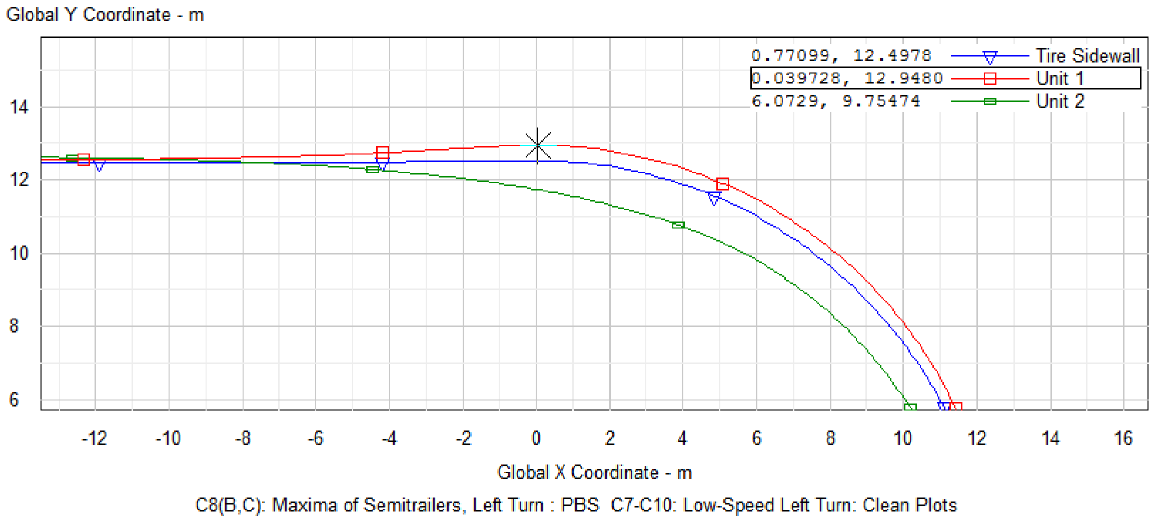


Figure 13. Plots of Y coordinate of corner points of all units.

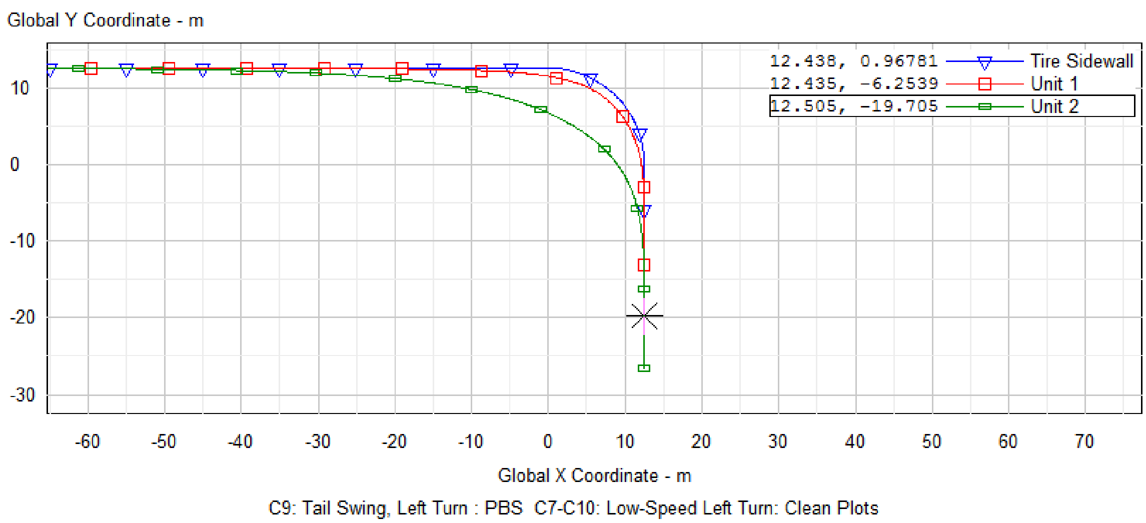


Figure 14. Plots of trajectories at start of turn to evaluate possible tail swing.

Steer-Tire Friction Demand (C10)

Friction demand is defined for a tire as the ratio of the combined shear force divided by the normal force. PBS Standard C10 specifies that friction demand be calculated for both tires on the front axle and expressed as a percentage. The TruckSim procedure adds three variables: the demand for both tires on the front axle, plus the demand for each tire individually. They can be viewed with the C10 friction plot (Figure 15).

> **Note** A plot for the Steer Tire Friction Demand for a single steer axle is defined in a **Procedures** dataset. If your vehicle has two front steer axles, please select the plot C10: Friction Demand (Axles 1 and 2) from the plot Category "PBS (Performance Based Standards)".

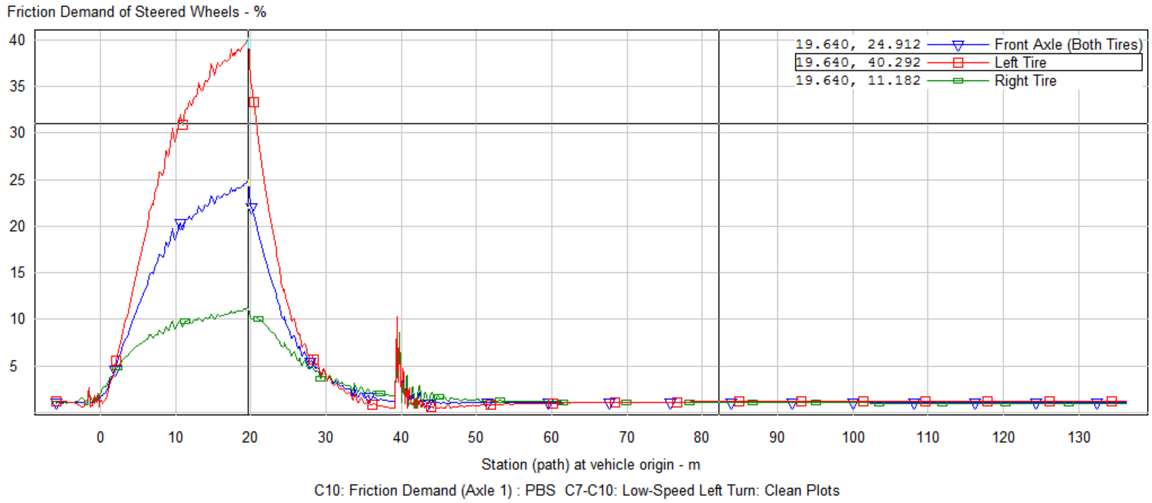


Figure 15. Friction demand for front tires.

Static Rollover Threshold (C11)

The purpose of this standard is to minimize safety risk by limiting the rollover tendency of a PBS vehicle during steady turns. Simulating a rollover in a steady turn is not easy if the powertrain has an open differential. This is because when the rollover limit is approached the inner wheels' lift, power is lost to the outer wheel(s) still on the ground, and the vehicle slows down until the inner wheels are back on the ground. At that point, the speed increases again and the process repeats.

For this reason, the rollover threshold is tested in TruckSim using a tilt table (Figure 16).

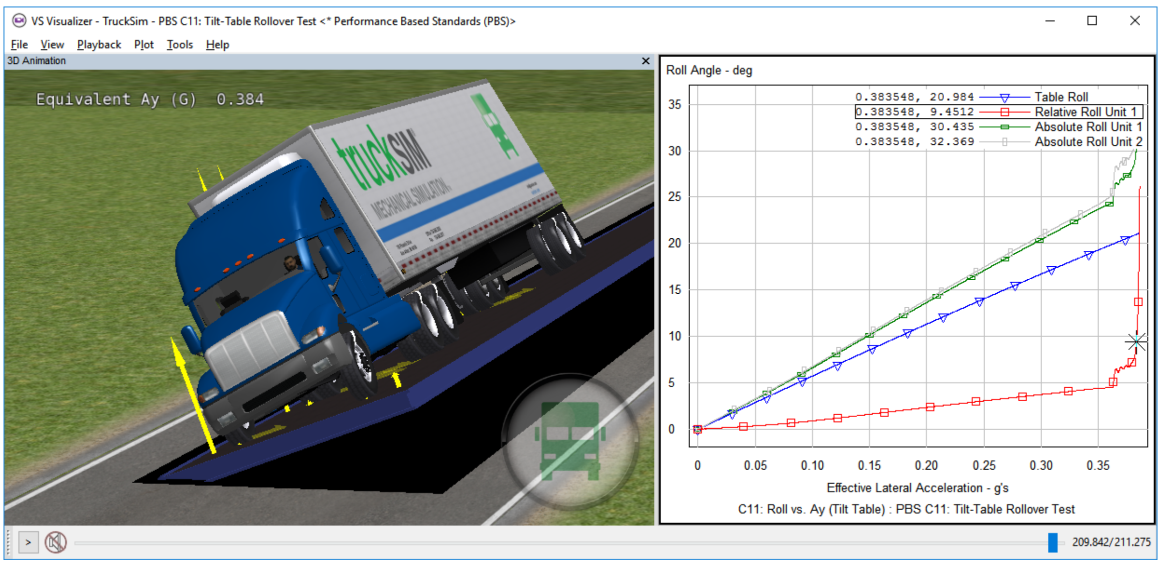


Figure 16. Animation and plot for a tilt table test.

Model Requirements

This test is quasi-static. Therefore, aerodynamics, steering system, and powertrain details have little or no influence on the test results. The behavior mainly depends on the, masses, their locations, and suspension data.

The brakes are used to immobilize the vehicle on the tilt table, but details of the system are not important; they are simply used to keep the wheels locked.

The tire models apply the shear forces to keep the vehicle fixed on the tilt table, but details of the behavior are not used (i.e., the contact points between the tire and ground do not move).

Setting Up the Run

Two links are needed on the TruckSim **Run Control** screen to set up the run.

Vehicle: Link to a dataset for the vehicle of interest in the fully loaded condition.

Procedure: Link to the **Procedures** dataset **PBS (Performance Based Standards)>PBS C11: Tilt Table Rollover Test**. This includes the tilt table and associated animation support.

Evaluating the Results

A quick evaluation is obtained from the plot of roll angle vs. equivalent lateral acceleration (Figure 16). The run is set to end when the absolute roll angle of the first sprung mass reaches 50°; this happens very quickly after the wheels lift off, so the highest level of equivalent lateral acceleration in the plot is a good estimate of the rollover threshold. For example, the HUD text in Figure 16 shows the effective lateral acceleration of 0.384 g's when all but the front wheels have lifted off.

Dynamic Lane Change (C12, C13)

A dynamic lane change maneuver is used to evaluate the transient behavior of combination vehicles (C12) and space needed by the rearmost trailer (C13). Both standards can be applied with two simulations for a given vehicle: one for a left lane change and one for a right lane change.

The vehicle is controlled to make a single lane change as described in ISO 14791:2000. ISO defines two ways to perform the test. The method used in TruckSim is to follow a target path for the first sprung mass origin, which is nominally at the center of the vehicle front axle. The built-in closed-loop steering control is set up to make this point follow a path, so this test can be defined simply by setting the target path in TruckSim to match the equation from ISO 14791:

$$y = \frac{a_y}{(2\pi f)^2}\left[2\pi f\,\frac{x}{v} - \sin\left(2\pi f\,\frac{x}{v}\right)\right]$$

The PBS standard sets the frequency parameter f to 0.4 Hz and the speed to 88 km/h (24.444 m/s), resulting in the waveform shown in Figure 17 (generated with the TruckSim **Calculator: Symbolic** library). Two revisions were made to the formula: first, the lateral acceleration a_y was set to unity to make a waveform that can be rescaled to other acceleration levels. Second, the curve is offset to start at $-1/(2\pi f^2)$, which causes it to finish with Y equal to zero.

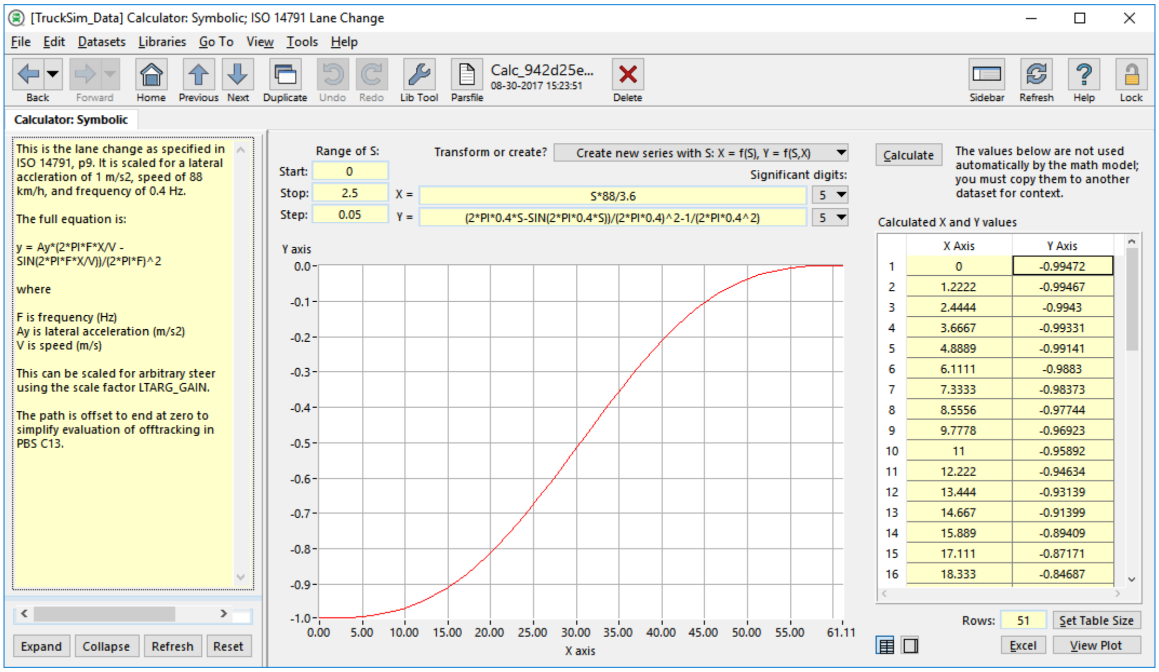


Figure 17. ISO lane change path for center of front axle.

Model Requirements

This test is performed at a constant target speed. Therefore, the brake system is not used, and the detailed powertrain model and aerodynamic drag do not heavily influence the vehicle's performance. All other parts of the TruckSim model are significant (tires, suspensions, steering, inertia properties).

Tracking of the simulated vehicle involves plotting the X and Y coordinates of the front and rear Motion Sensors on each side of each sprung mass unit (Table 2, page 4).

Setting Up the Run

Two links are needed on the TruckSim **Run Control** screen to set up the run.

Vehicle: Link to a dataset for the vehicle of interest in the fully loaded condition, with links to Motion Sensors for each vehicle unit (i.e., lead unit and trailer(s)).

Procedure: Link to the **Procedures** dataset **PBS (Performance Based Standards)>ISO 14791 Lane Change Scaled to Ay Target**.

Rearward Amplification (C12)

The purpose of this standard is to minimize safety risk by limiting the lateral-directional response of a multi-articulated PBS vehicle in avoidance maneuvers performed at highway speed without braking.

To evaluate the success of the test, first examine the TruckSim plot for the tracking error of the front axle to ensure that the steering controller maintained the axle centerline within 30 mm of the intended path. For example, Figure 18 was generated using the 3-axle dump truck towing a 2-axle dolly with a 2-axle dump trailer. The results show that the tracking error was about +18/-25 mm, and is therefore with the tolerances. If the vehicle does not track accurately, you will need to adjust the driver path follower parameters on the **Controls: Steering by Closed-loop Driver Model** screen. Normally, decreasing the preview time will make the vehicle track more accurately, diminishing the error. However, decreasing the preview time also has the effect of making the controller less stable.

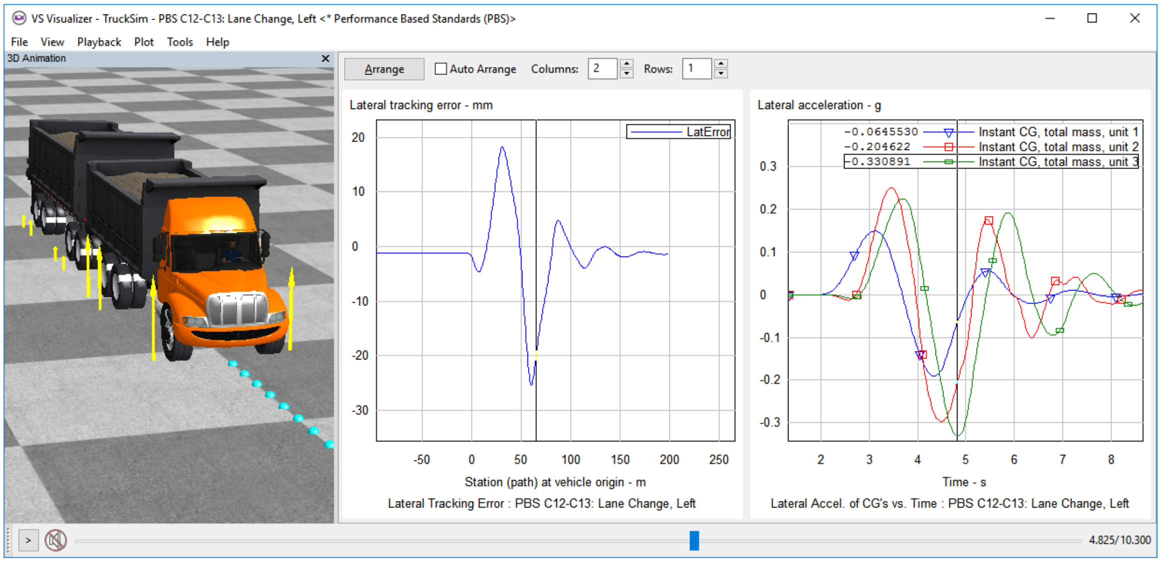


Figure 18. Tracking of the center of the front axle in ISO 14791.

Once a successful test has been made, consult the plot of lateral acceleration of the sprung mass centers of gravity. The example here shows smooth traces of lateral acceleration for each of the three vehicle units: the 3-axle dump truck, the 2-axle dolly, and the 2-axle trailer.

Certain vehicle combinations might show spikes in the lateral acceleration that may require some interpretation. The TruckSim math model has lash in the hitch connections, so when the limit of the hitch is reached the impact generates a pulse in acceleration.

High-Speed Transient Off-tracking (C13)

The purpose of this standard is to minimize safety risk by limiting the sway of the rearmost trailers of multi-articulated PBS vehicles in avoidance maneuvers performed without braking at highway speeds.

Because the target path for the vehicle is along the global X axis (Figure 17), all that is needed to evaluate the transient off-tracking after the lane change is a plot of the global Y coordinates of the axle centers (Figure 19). Find the largest Y value and that is the maximum off-tracking. In this example, the maximum is for axle 4, with a Y coordinate of 0.425m.

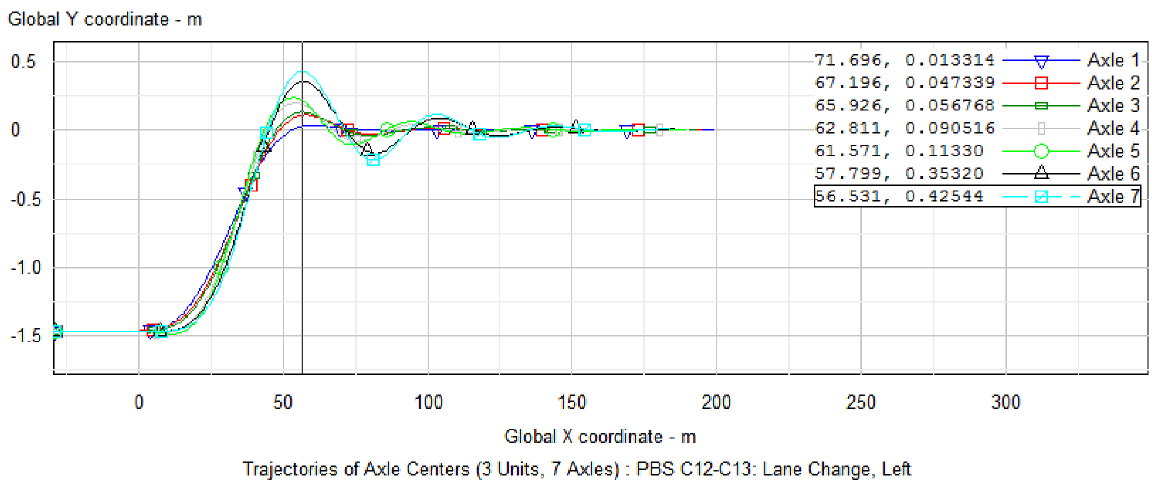


Figure 19. Transient off-tracking of axle centers.

Yaw Damping (C14)

The purpose of this standard is to minimize safety risk by requiring acceptable attenuation of any sway oscillations of rigid PBS vehicles or between the trailers of multi-articulated PBS vehicles.

This standard is also based on ISO 14791. However, in this case the pulse-steer test is used rather than the lane change. The steering pulse waveform is defined in Appendix E of the NTC PBS Scheme document as:

$$\delta(t) = \delta_m [0.5 - \cos(2\pi t/0.6)]$$

where t is the time from the start of the pulse for a duration of 0.6 seconds. Before the pulse starts and after it finishes, δ(t) is zero. This waveform was created in the TruckSim **Calculator: Symbolic** library, normalized for an amplitude of 1 (Figure 20).

Model Requirements

This test is performed at a constant target speed. Therefore, the brake system is not used, and the detailed powertrain model and aerodynamic drag do not heavily influence the vehicle's performance. All other parts of the TruckSim model are significant (tires, suspensions, steering, inertia properties). The level of detail needed for this standard is the same as needed for the lane change tests C12 and C13.

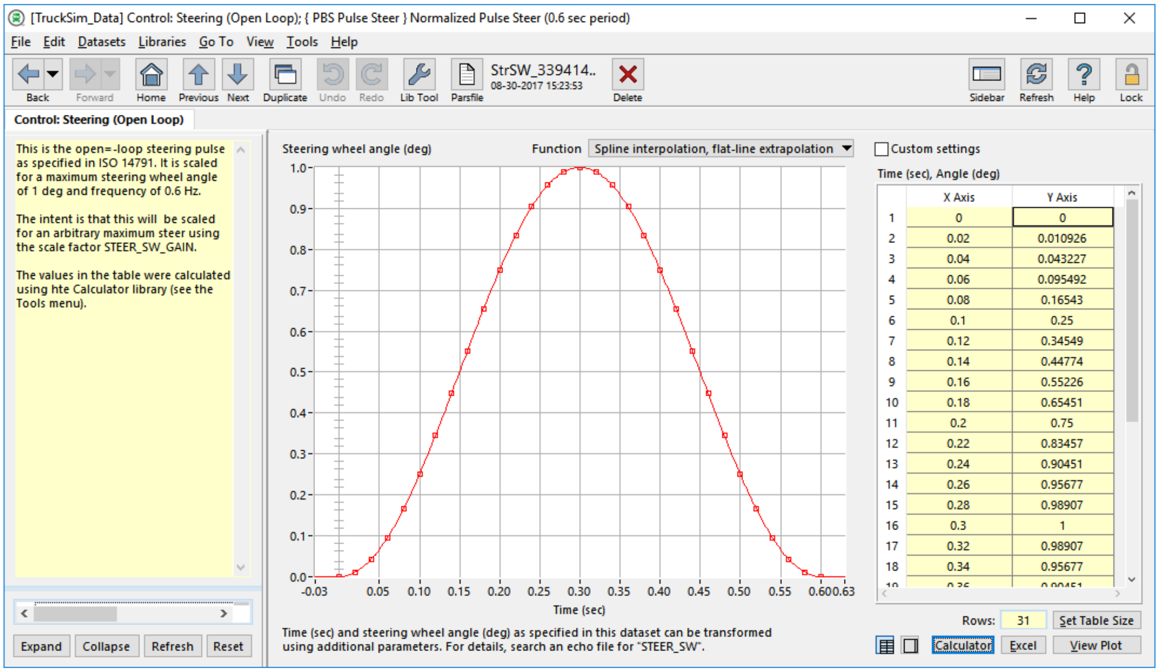
Setting Up the Run

This test may need to be customized slightly for each vehicle. ISO 14791 mentions test speeds of 80, 90, and 100 km/h. For any given speed, the steering pulse is to be scaled such that the lateral acceleration of the lead unit reaches a peak of 2 m/s^2 (0.20 g's).

Two links are needed on the TruckSim **Run Control** screen to set up the run (Figure 21).

Vehicle: Link to a dataset for the vehicle of interest in the fully loaded condition 1.

Procedure: Link to the **Procedures** dataset **PBS (Performance Based Standards)>PBS C14: Yaw Damping** 2.



	X Axis	Y Axis
1	0	0
2	0.02	0.010926
3	0.04	0.043227
4	0.06	0.095492
5	0.08	0.16543
6	0.1	0.25
7	0.12	0.34549
8	0.14	0.44774
9	0.16	0.55226
10	0.18	0.65451
11	0.2	0.75
12	0.22	0.83457
13	0.24	0.90451
14	0.26	0.95677
15	0.28	0.98907
16	0.3	1
17	0.32	0.98907
18	0.34	0.95677

Figure 20.Normalized steering pulse for yaw-rate evaluation.

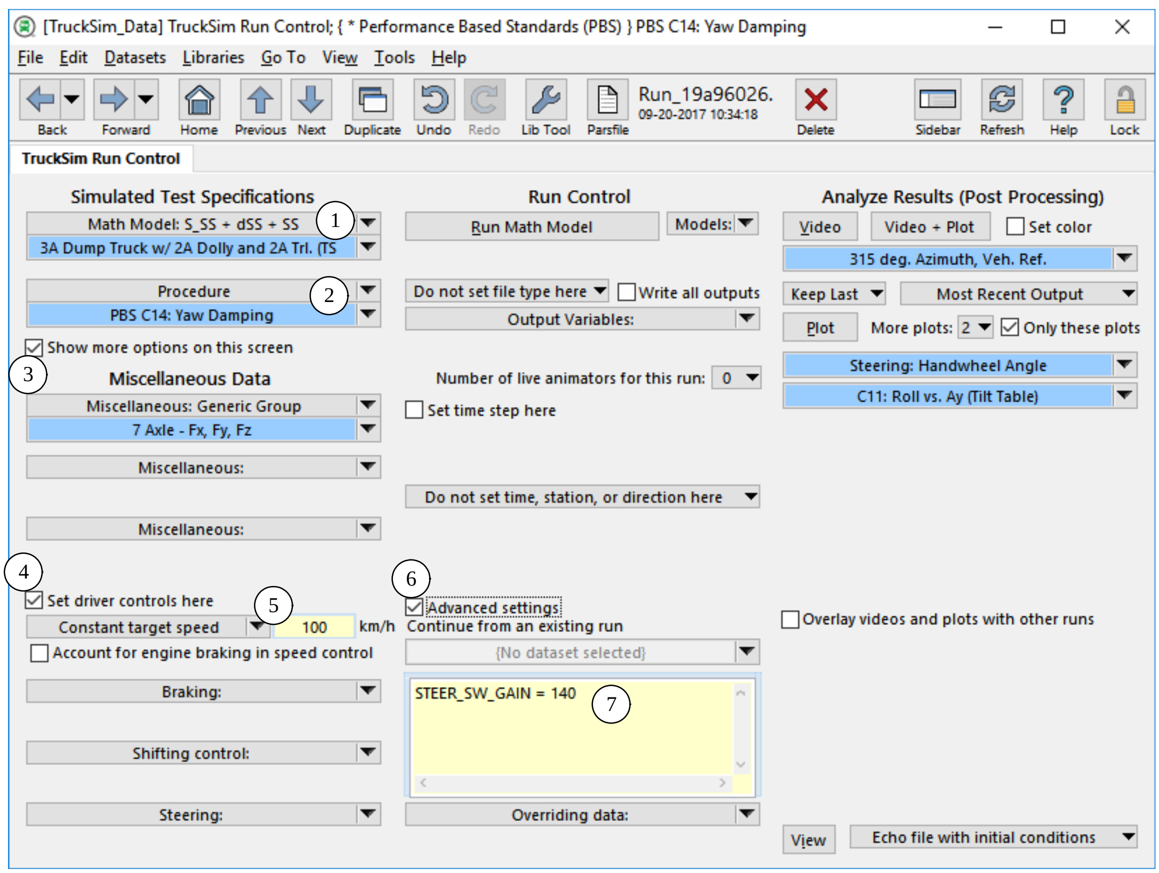


Figure 21. Setting up a run to evaluate yaw damping.

Two other settings are made on the **Run Control** screen: the speed and the amplitude of the steering pulse. To make these controls visible, three checkboxes must be checked: 3, 4, and 6. Use the first driver control to specify the target speed for the closed-loop speed controller 5. Use the miscellaneous yellow field to scale the open-loop steering wheel angle with the keyword `STEER_SW_GAIN` 7.

Evaluating the Results

The yaw rate damping is an assumed linear property of what is actually a nonlinear system (i.e., the vehicle). If the steering pulse is too small, friction in the vehicle suspension and lash in the hitches can cause the response to be far from the intended linear-like behavior. If the steering pulse is too large, the rearmost unit's tires might lift off or even roll over.

Ideally, you can look at the plot of lateral acceleration of the first sprung mass and estimate how much to adjust the steering pulse amplitude in order to obtain a lateral acceleration peak near 0.20 g's. However, if the response of the rear unit is too extreme, a lower acceleration limit is acceptable. If vehicle stability is a problem, the speed can be lowered.

Details for evaluating the response are provided in both Appendix C of the PBS Scheme document and in ISO 14791.

Directional Stability Under Braking (C16)

The primary purpose of this standard is to manage safety risk of vehicle instability when braking in a turn or on pavement cross slopes.

The standard specifies several levels of deceleration, ranging from 0.40 g's (rigid trucks and buses) down to 0.20 g's PBS Level 4 vehicles.

The simulated braking test is made to achieve the target deceleration, and friction utilization is monitored for each axle group.

Model Requirements

This test makes use of most features of a TruckSim vehicle model. It is the only standard in which the brake system plays a significant role. Because the brake test is in a straight line, starting from about 65 km/h, details of the powertrain, steering system, and aerodynamics are not critical in this case.

This test is typically applied for an unloaded vehicle, although vehicles of the type selected for this example – dump truck and trailers— are more commonly run when full than empty. Testing with a loaded vehicle necessarily puts more demands on the tires and brake system, as well as influences the load distribution on the axles, suspensions, and tires.

Setting Up the Run

This test is typically adjusted for each vehicle to set the brake pressure applied during the test.

Two links are needed on the TruckSim **Run Control** screen to set up the run (Figure 22).

Vehicle: Link to a dataset for the vehicle of interest in either the unloaded or loaded condition 1.

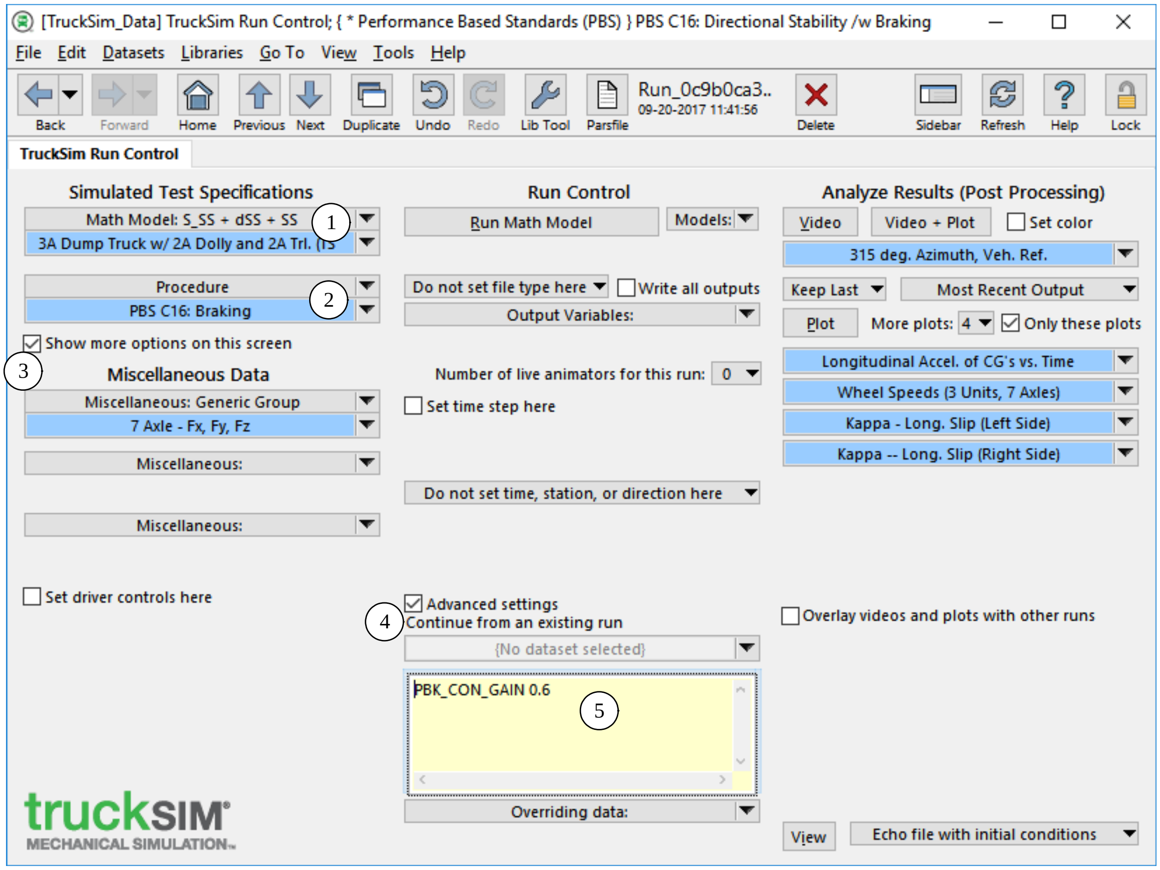


Figure 22. Setting up a run to evaluate directional stability under braking

Procedure: Link to the **Procedures** dataset **PBS (Performance Based Standards)>PBS C16: Braking** 2.

In addition, boxes are checked (3 and 4) to display the miscellaneous yellow field under **Advanced settings** 5. The braking procedure 2 is set up to apply pressure at the master cylinder of 1 MPa at t = 2s. This allows the pressure to be rescaled with the keyword `PBK_CON_GAIN` in the miscellaneous field 5. For example, the gain is set to 0.6 in the figure, resulting in pressure 0.6 MPa at t = 2s.

Evaluating the Results

Plots of longitudinal acceleration should be viewed after the first simulation run. Adjust the brake pressure gain 5 as needed to obtain the desired deceleration in subsequent simulations.

The main performance level to be checked with this test is lockup of wheels during braking, when the brakes are at a sufficient level to achieve the deceleration specified in the PBS standard. All wheel speeds can be plotted in TruckSim (Figure 23, Figure 24). In the plots, wheel angular velocity is converted to equivalent translational speed in km/h for comparison with vehicle speed.

The run made for Figure 24 used a vehicle with no ABS control on the trailers, and with a brake pressure high enough to trigger lockup. Lockup is seen easily as the speed drops to zero.

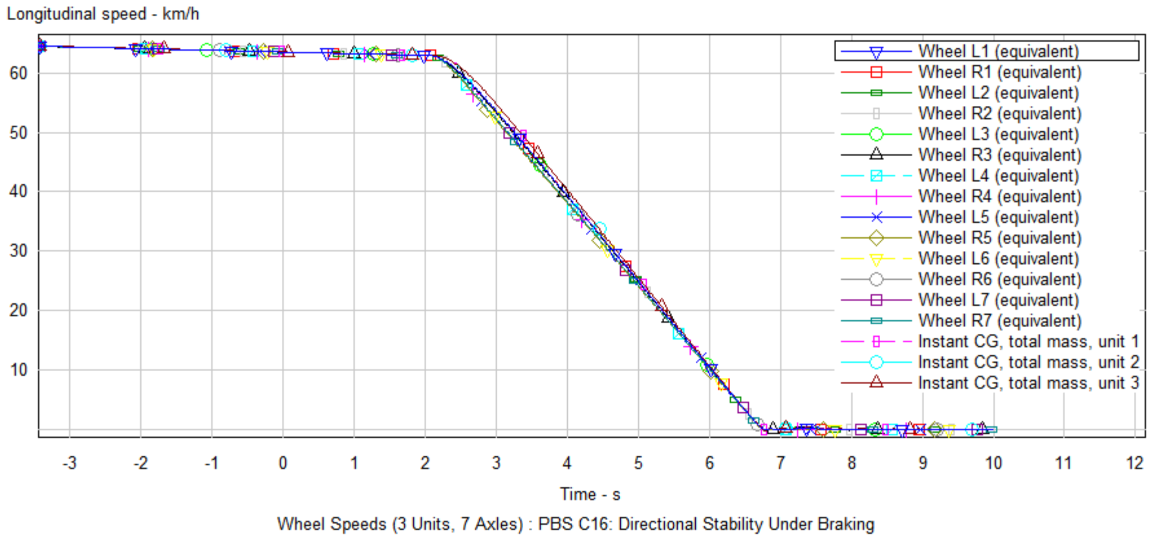


Figure 23. Wheel speeds when no lockup occurs.

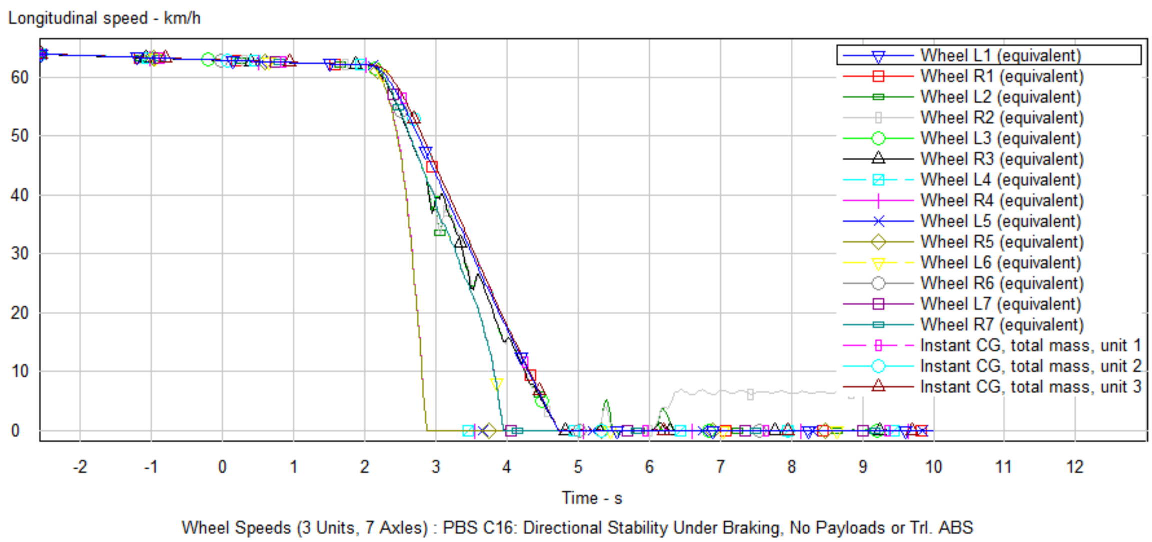


Figure 24. Wheel speeds showing lockup on axles 4-7 (trailers w/o ABS).

Appendix E in the PBS Scheme also specifies that the friction utilization be calculated for each group of axles. Because the grouping of axles is specific to each vehicle configuration, it is not easy to provide utilization of axle groups in a single generic brake procedure. However, a quick assessment can be made by looking at the longitudinal slip for all tires (Figure 25). When a wheel is locked, the slip goes to -1. Maximum friction utilization occurs somewhere when the slip magnitude exceeds +/- 0.1. The slip ratios for the case where none of the tires approach their frictional limits are shown in Figure 26.

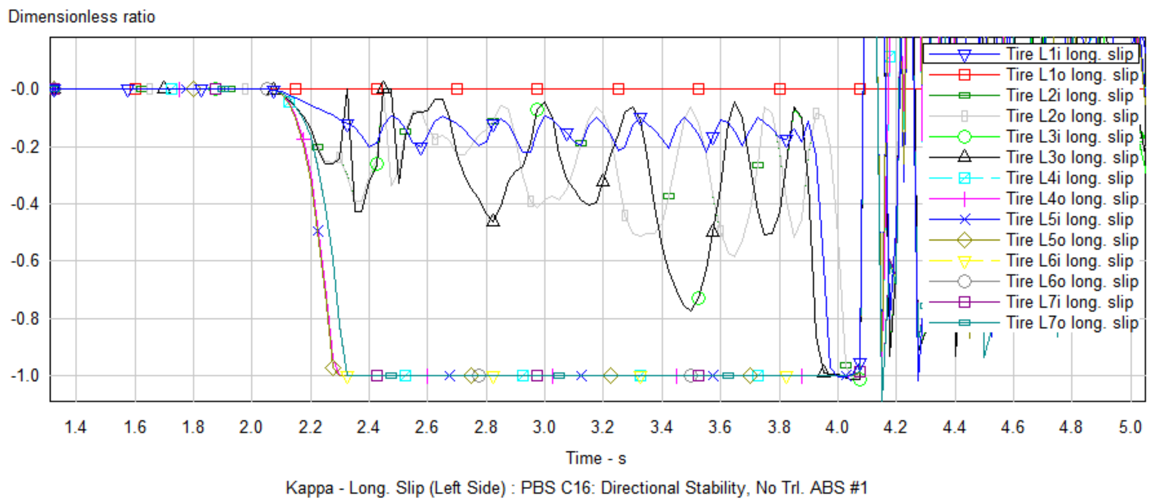


Figure 25. Longitudinal slip during braking with locked wheels.

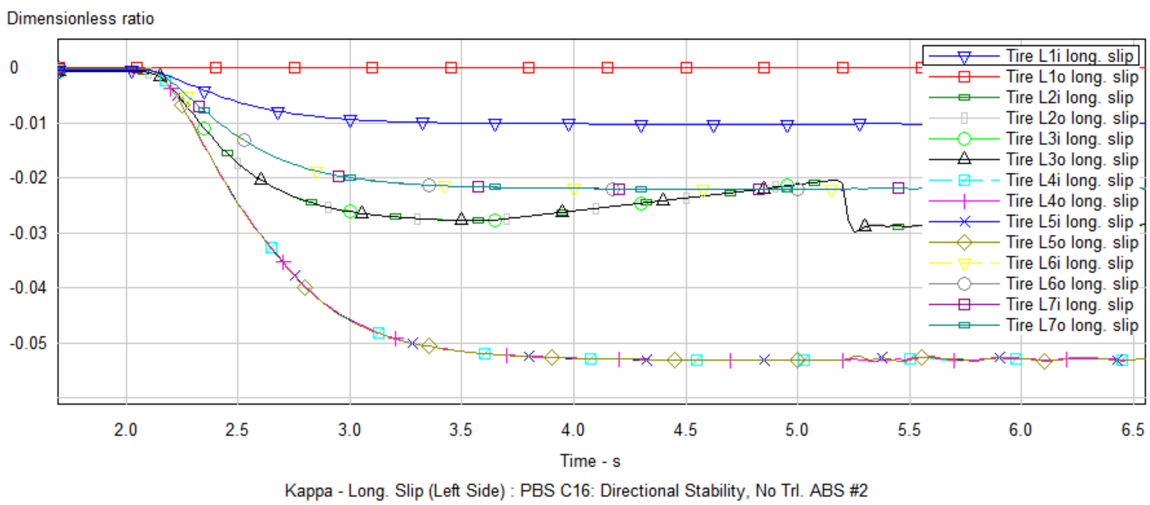


Figure 26. Longitudinal slip during braking without approaching frictional limits.

References

1. National Transport Commission, “Performance Based Standards Scheme: The Standards and Vehicle Assessment Rules” (*PBSSchemeStandsVehAssRule24Nov08.pdf*), http://www.ntc.gov.au; Melbourne, Australia, 2008.

2. Duprey, B., Sayers, M., and Gillespie, T., "Using TruckSim to Test Performance Based Standards (PBS)," SAE Technical Paper 2012-01-1919, 2012, doi:10.4271/2012-01-1919.

3. Duprey, B., Sayers, M., and Gillespie, T., "Simulation of the Performance Based Standards (PBS) Low-Speed 90° Turn Test in TruckSim by Jumping Back in Time," SAE Technical Paper 2013-01-2374, 2013, doi:10.4271/2013-01-2374.

Appendix A: Control Strategy Flow Chart for Low Speed Turn test

Begin Test

- Define:
  - Tire reference point location
  - Calculate X and Y tracking for tire sidewall reference point
  - Calculate Lateral Tracking Error using X and Y tracking from above. This is the distance (i.e. error) from the tire reference location to the 12.5-m target path.
  - Initial lateral offset between 12.5-m turn target path and driver model vehicle reference location (i.e., center of front axle) = ½ track width + ½ tire width (i.e. tire reference point)
- Drive at 5 km/h, following target path for 90 degree turn

↓

Event A: Check Tracking Error

- Define:
  - Lateral tolerance, used for comparison to Lateral Tracking Error. This is how far the tire reference point is allowed to be from the calculated path.
  - Distance to jump back
  - Lateral target limit (from 12.5-m turn target path)
  - Number of allowable iterations
- One of three possibilities exist, in the following order.

If the Lateral Tolerance < abs(Lateral Tracking Error) → Event B. Tracking Error Hit. Adjust target and try again

If the current iteration > maximum number of allowable iterations → End Events

If Lateral Target Limit < abs(Lateral Target Offset) → End Events

Event B. Tracking Error Hit. Adjust target and try again

- Recalculate the lateral target offset for the closed-loop driver model by adjusting the offset by ½ of the Lateral Tracking Error.
- Restore_State by jumping back the specified distance.

If the Lateral Tolerance < abs(Lateral Tracking Error)

- Reload this Event and keep trying until:
  - The vehicle successfully completes the maneuver, or
  - The maximum number of iterations is reached, or
  - The vehicle's abs(Lateral Target Offset) > user-defined Lateral Target Limit

Appendix B: Index of Selected VS Commands and TruckSim Variables

Note regarding units: TruckSim performs all calculations using the SI system of units (i.e., length in meters, time in seconds, angles in radians, etc.).

LatError: Lateral error. Formula used to calculate the lateral distance between the target path for the driver-model and a point defined with coordinates Xctc_R1o and Yctc_R1o. User-defined.

LatTol: Lateral tolerance limit, used in the control strategy to decide when the tire's reference point has exceeded the allowable distance from the specified 12.5-m path. User-defined and based on the PBS specifications.

L_Tire_Ref: Reference point at the tire's outermost sidewall, measured from the wheel-plane center. User-defined based on tire specifications.

Path_L_I: TruckSim built-in function. This is the lateral offset L of a point defined by X and Y coordinates, relative to the driver reference path.

S_Back: Distance parameter, used to decide how far back the vehicle should be placed using the RESTORE_STATE command. User-defined and adjustable based on the vehicle data being tested.

T: Simulation time

Vx: TruckSim variable for forward vehicle speed

Xctc_R1o: X-coordinate, center of tire contact, right front tire

Yaw_R1: Yaw, right-front wheel

Yctc_R1o: Y-coordinate, center of tire contact, right front tire