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TruckSim Steering Systems

What is Steer?

Steer refers to one aspect of the angular orientation of a wheel in the coordinate system of a vehicle (the others are *camber* or *inclination*, and *spin*). Specifically, steer is the angle from the vehicle longitudinal axis (in TruckSim the X axis) to a line formed by the intersection of the plane of the wheel with the vehicle horizontal plane (in TruckSim the X-Y plane). In TruckSim, all wheels on any axle may be steered. Steer of trailer axles is not supported by the TruckSim Browser but can be implemented using VS Commands by advanced users.

Steer is contributed by several sources. First and most obvious is the output of the vehicle and axle *steering system* if one is present. The steering system transforms a steering command applied to the vehicle steering wheel (or other input) into steer of the road wheel. Internally, the steering system may or may not have dynamic elements (differential equations and their integrals) and may or may not depend on applied forces. This part of steer may be called *active steer*.

The second source of steer at a wheel is the kinematic behavior of the suspension system. This steer occurs whether a steer command is present or not. It is typically called ride steer, ride toe, roll steer, or roll toe. Here, toe is taken by tradition to mean steer motion with opposite sign at the two wheels on an axle. When both wheels steer toward the vehicle centerline the effect is called *toe in* or positive toe. When both wheels steer away from the vehicle centerline the effect is called *toe out* or negative toe. (Note the magnitude of steer on the two sides need not be equal, that is, the effect may be asymmetric.)

The third source of steer at a wheel is motion resulting from elastic deformation of components (primarily elastic bushings, but also including structural deformation) due to applied forces, mainly tire forces. Known as *compliance steer* or *compliance toe*, it is typically characterized by coefficients describing the ratio of the change in steer of the wheel per unit change of a component of applied force.

The second and third sources of steer listed above may be called *passive steer* because they occur with no commanded change in steer.

The TruckSim Steering System deals with steer in response to commanded inputs, including kinematic elements and dynamic behaviors, if there are any. In other words, it deals with *active steer*. *Passive steer* is provided by the suspension system (though one of the compliances is characterized on the screen with the rest of the steering system properties).

Parameters are entered into data fields on the Steering System screen to describe many of the system's properties and configurable functions are used to describe many others. Each configurable function is represented with a separate library screen, as summarized in Table 1. (See the *VehicleSim Browser Reference Manual* for a description of configurable function screens and their various options.)

The TruckSim Steering System in Concept

The Steering System offers many options to represent most configurations offered on trucks today. An advanced user can also replace elements of the system with his own definitions from VS Commands or external code such as Simulink.

These options will be outlined here and discussed in more detail later in this document.

The first, most fundamental option is a choice of whether the wheels on an axle can be actively steered at all. The TruckSim Browser sets the value of a parameter, `OPT_STEER_EXT`, to zero (actively steered) or one (not actively steered) to set this choice, except for advanced applications that replace elements of the steer system with externally defined sub-systems.

Second, a TruckSim steering system can be either an *Asymmetric* system, typical of heavy trucks, in which the steer of one wheel (left or right) is a function of the output of the steering gear with the opposite wheel steered by a tie rod linking the two sides, or it can be a system that is more typical of light- and medium-duty trucks identified in the browser as *Symmetric*. Symmetric steer supports recirculating ball or rack and pinion steering gears. The term "symmetric" doesn't imply that the kinematic behavior of the two sides must be identical, but only that the output of the steering gear (pitman arm rotation or rack translation) drives each wheel individually through tie rods or linkages. Other than the availability of the rack and pinion, the primary difference between symmetric and asymmetric options is in the calculation of compliance effects.

An actively steered axle specified as *Symmetric* may make use of either a *Rack and Pinion* or *Recirculating Ball* steering gear. Several points are notable: Though the term *Recirculating Ball* is used in the Browser and manuals, the actual gear might have any of several configurations, such as *Worm and Roller* or *Worm and Sector*. The only significant feature is that the input and output of the gear are both rotations, while the *Rack and Pinion* has rotation as an input and translation as an output. The location of the steering system (behind or ahead of the axle) is implied by the user's choice of sign conventions for the various properties.

Third, the first axle may be designated as *Power* or *Manual*. All other steered axles are treated as under servo control, and only the first axle contributes to torque at the steering wheel. Axles with power boost systems receive an additional degree of freedom because a torsional spring (*torsion bar*) is inserted between the control input (steering column rotation) and the input to the gear. The torque in the spring is input to a table of boost force (or torque) to obtain the boost level.

Several minor options are provided. The steering wheel torque may be read from a table of torque as a function of the sum of the steering axis (kingpin) torques, or it may be calculated from the system kinematics, boost (if any), damping, and hysteresis. A table may be linked to specify an additional component of steer torque to be added as a function of speed, to reflect the higher torques exhibited in, for example, parking maneuvers. And the definition of "steer" may be referenced in the vehicle coordinate system as described above, or as a rotation about the steering axis. The second choice is rarely used, but might be in the case of, for example, experimental data taken by instruments measuring the angle about the steer axis.

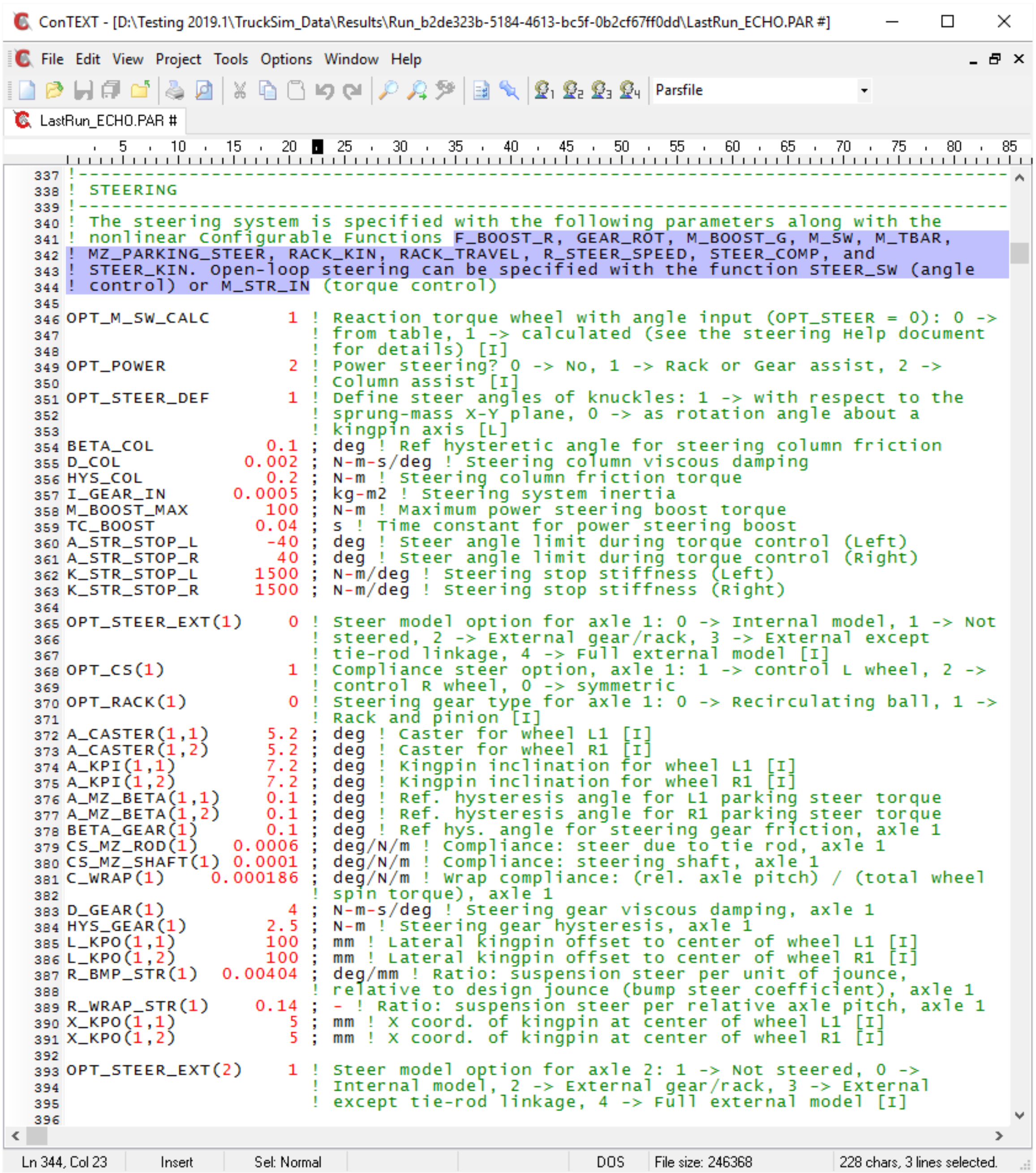
The steering of the wheels is determined by properties of both the steering system and the suspension. The steering system model contains considerable detail, including a full multibody representation of the steered wheels, and a power steering system. It also distinguishes between rack and pinion steering and recirculating ball steering systems.

The steering system includes kinematical and compliance effects. Kinematical effects are steer motions depending only on the positions of components (the steering wheel or rack position, for example). Compliance effects are steer motions caused by forces and moments within or applied to the steering system or road wheels. The two are combined to determine the steer angle of each wheel in addition to steer effects caused by suspension motion.

Parameters describing the steering systems are split into two groups: those that describe the column or system-wide properties, and those that are specified for each steered axle.

Parameters pertaining to the steering column, boost and system-wide properties appear on the **Steering Column and Assist** screen.

Parameters that describe the interactions between suspension movements and steer angle are contained in the steering screens for each axle. These include the steering axis (kingpin) geometry, the gear type and ratio (each steered axle has its own steering gear), the wheel-end kinematic properties, and a table to modify the steering control as a function of the driver input and vehicle speed. These parameters are listed in the Steering section of the Echo file produced for each simulation (Figure 1).




```
337 !------------------------------------------------------------------------------
338 ! STEERING
339 !------------------------------------------------------------------------------
340 ! The steering system is specified with the following parameters along with the
341 ! nonlinear Configurable Functions F_BOOST_R, GEAR_ROT, M_BOOST_G, M_SW, M_TBAR,
342 ! MZ_PARKING_STEER, RACK_KIN, RACK_TRAVEL, R_STEER_SPEED, STEER_COMP, and
343 ! STEER_KIN. Open-loop steering can be specified with the function STEER_SW (angle
344 ! control) or M_STR_IN (torque control)
345
346 OPT_M_SW_CALC        1 ! Reaction torque wheel with angle input (OPT_STEER = 0): 0 ->
347                        ! from table, 1 -> calculated (see the steering Help document
348                        ! for details) [I]
349 OPT_POWER            2 ! Power steering? 0 -> No, 1 -> Rack or Gear assist, 2 ->
350                        ! Column assist [I]
351 OPT_STEER_DEF        1 ! Define steer angles of knuckles: 1 -> with respect to the
352                        ! sprung-mass X-Y plane, 0 -> as rotation angle about a
353                        ! kingpin axis [L]
354 BETA_COL           0.1 ; deg ! Ref hysteretic angle for steering column friction
355 D_COL            0.002 ; N-m-s/deg ! Steering column viscous damping
356 HYS_COL            0.2 ; N-m ! Steering column friction torque
357 I_GEAR_IN       0.0005 ; kg-m2 ! Steering system inertia
358 M_BOOST_MAX        100 ; N-m ! Maximum power steering boost torque
359 TC_BOOST          0.04 ; s ! Time constant for power steering boost
360 A_STR_STOP_L       -40 ; deg ! Steer angle limit during torque control (Left)
361 A_STR_STOP_R        40 ; deg ! Steer angle limit during torque control (Right)
362 K_STR_STOP_L      1500 ; N-m/deg ! Steering stop stiffness (Left)
363 K_STR_STOP_R      1500 ; N-m/deg ! Steering stop stiffness (Right)
364
365 OPT_STEER_EXT(1)     0 ! Steer model option for axle 1: 0 -> Internal model, 1 -> Not
366                        ! steered, 2 -> External gear/rack, 3 -> External except
367                        ! tie-rod linkage, 4 -> Full external model [I]
368 OPT_CS(1)            1 ! Compliance steer option, axle 1: 1 -> control L wheel, 2 ->
369                        ! control R wheel, 0 -> symmetric
370 OPT_RACK(1)          0 ! Steering gear type for axle 1: 0 -> Recirculating ball, 1 ->
371                        ! Rack and pinion [I]
372 A_CASTER(1,1)      5.2 ; deg ! Caster for wheel L1 [I]
373 A_CASTER(1,2)      5.2 ; deg ! Caster for wheel R1 [I]
374 A_KPI(1,1)         7.2 ; deg ! Kingpin inclination for wheel L1 [I]
375 A_KPI(1,2)         7.2 ; deg ! Kingpin inclination for wheel R1 [I]
376 A_MZ_BETA(1,1)     0.1 ; deg ! Ref. hysteresis angle for L1 parking steer torque
377 A_MZ_BETA(1,2)     0.1 ; deg ! Ref. hysteresis angle for R1 parking steer torque
378 BETA_GEAR(1)       0.1 ; deg ! Ref hys. angle for steering gear friction, axle 1
379 CS_MZ_ROD(1)    0.0006 ; deg/N/m ! Compliance: steer due to tie rod, axle 1
380 CS_MZ_SHAFT(1)  0.0001 ; deg/N/m ! Compliance: steering shaft, axle 1
381 C_WRAP(1)     0.000186 ; deg/N/m ! Wrap compliance: (rel. axle pitch) / (total wheel
382                        ! spin torque), axle 1
383 D_GEAR(1)            4 ; N-m-s/deg ! Steering gear viscous damping, axle 1
384 HYS_GEAR(1)        2.5 ; N-m ! Steering gear hysteresis, axle 1
385 L_KPO(1,1)         100 ; mm ! Lateral kingpin offset to center of wheel L1 [I]
386 L_KPO(1,2)         100 ; mm ! Lateral kingpin offset to center of wheel R1 [I]
387 R_BMP_STR(1)   0.00404 ; deg/mm ! Ratio: suspension steer per unit of jounce,
388                        ! relative to design jounce (bump steer coefficient), axle 1
389 R_WRAP_STR(1)     0.14 ; - ! Ratio: suspension steer per relative axle pitch, axle 1
390 X_KPO(1,1)           5 ; mm ! X coord. of kingpin at center of wheel L1 [I]
391 X_KPO(1,2)           5 ; mm ! X coord. of kingpin at center of wheel R1 [I]
392
393 OPT_STEER_EXT(2)     1 ! Steer model option for axle 2: 1 -> Not steered, 0 ->
394                        ! Internal model, 2 -> External gear/rack, 3 -> External
395                        ! except tie-rod linkage, 4 -> Full external model [I]
396
```

Figure 1. Steering section of Echo file that lists parameters and names Configurable Functions.

Configurable functions are used to describe many properties of steering systems and components. Note that the names of the functions are also given in the comments at the start of the Steering section in the Echo file (lines 341 – 344, Figure 1). Each is represented with a separate library screen, as summarized in Table 1. One exception is that the torsion bar stiffness is represented in the math model using the Configurable Function `M_TBAR`, but the GUI supports a linear coefficient as identified with the keyword M_TBAR_COEFFICIENT. Advanced users may link to a Generic Table dataset to specify torque as a nonlinear function of twist.

Table 1. Summary of steering table libraries.

Library Screen	**Root Keyword(s)**	**Description**
Steering: Parking Torque	MZ_PARKING_STEER	Low speed and parking torque
Steering: Parking Torque for 2 Wheels		
Steering System: Compliance	STEER_COMP	Steer angle due to kingpin moments
Steering System: Gear Kinematics	GEAR_ROT	
ISHAFT_KIN	Steering gear output rotation vs input rotation, Intermediate shaft output rotation vs input rotation	
Steering System: Rack Kinematics	RACK_TRAVEL	
ISHAFT_KIN	Steering rack displacement vs pinion rotation, Intermediate shaft output rotation vs input rotation	
Steering: Power Assist Force	F_BOOST_R	Power assist force applied to steering rack
Steering: Power Assist Torque	M_BOOST_G	Power assist torque applied to steering gear (recirc. ball)
Steering System: Kinematics for One Wheel	STEER_KIN	Road wheel steer vs pitman arm rotation
Steering System: Kinematics for 2 Wheels (Recirc. Ball)		
Steering System: Kinematics for 2 Wheels (Rack & Pinion)	RACK_KIN	Road wheel steer vs rack displacement
Steering System: Rear-Wheel Gain	R_STEER_SPEED	Gain on rear steering control input
Steering Wheel Torque	M_SW	Steering wheel torque vs kingpin moment

Please see the *VehicleSim Browser Reference Manual* for a description of configurable function screens and their various options.

The Steering System Models in Detail

TruckSim offers five steering systems. The Asymmetric system maybe be specified as applying primary control (gearbox output) to either the left or right side. Two options are offered for each power assisted system (assist applied to the output side of the gear or applied to the column or input side). Asymmetric or symmetric steer is selected using the pulldown control on the **Steering System** screen shown in Figure 2. The choice of power steering (if any) is made using the pulldown control on the **Steering Column and Assist** screen shown in Figure 3. Each option is described below.

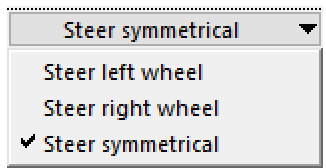


*Figure 2. Asymmetry / Symmetry Selection, **Steering System** screen.*

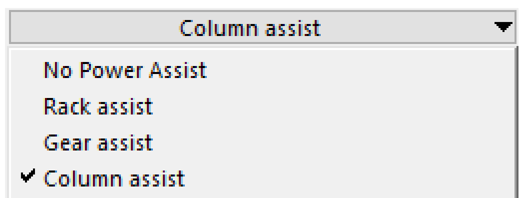


*Figure 3. Steering System Selection, **Steering Column and Assist** screen.*

Manual Asymmetric Steer

Figure 4 shows a schematic of a Manual (e.g., no assist) Asymmetric steering system. These systems are typical of heavy truck steering. Due to the lateral tie rod connecting the two wheels, they are used exclusively on solid axles. Either the left or right wheel may receive primary control, but for the sake of brevity only left wheel control is shown. If your simulations don't require detailed information about steer torque and deflection, it is recommended you use one of the manual steering options.

The system definition and its equations are the same for both left- and right- hand drive systems.

The Manual Asymmetric system elements are:

1. Steering Column Inertia. This consists of the column components from the steering wheel to the pinion, but not including the pinion.

2. Steering Column Friction. A constant torque due to rotating friction that always opposes the direction of rotation. It requires a reference angle representing about one third of the width of the hysteresis loop observed when the direction of travel is reversed.

3. Steering Column Damping. A torque in proportion to the steering column angular rate, opposing the direction of rotation.

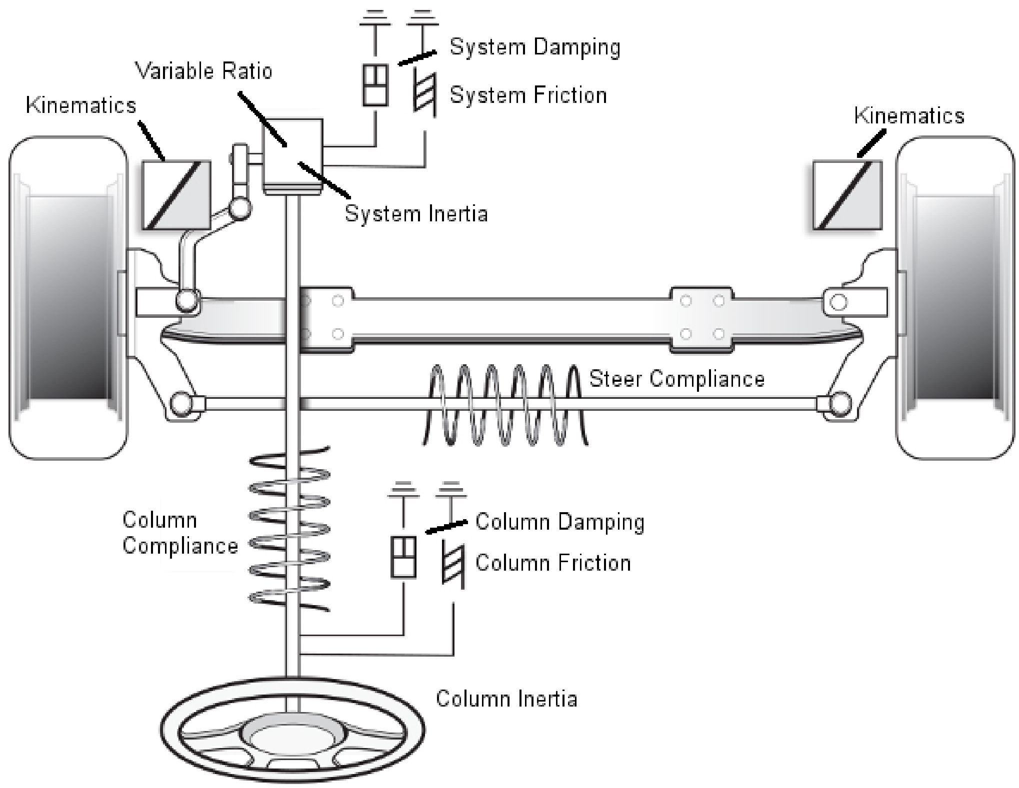


Figure 4. Manual Asymmetric Steer.

4. Steering gear ratio. This is the input (steering wheel) angle per degree of output (Pitman arm) angle. The relationship is internally represented by a table (configurable function) whose input is degrees of steering input gear rotation and output is degrees of Pitman arm rotation. In a manual system, the input gear angle and steering wheel angle (possibly modified by intermediate shaft kinematics) are the same.

5. (Optional) Intermediate shaft kinematics. The geometry of the intermediate shaft and its joints causes the output angle to lead or lag the input rotation, expressed here as a table of output rotation versus input rotation.

6. Steering Column Compliance. In manual (no power assist) systems, the steering column typically exhibits some angular compliance when torque is applied.

7. System Inertia. Includes the effect of the mass and inertia of the relay rod, tie rods, Pitman arm, idler arm, etc. expressed as a rotational inertia indexed to the input speed, plus the actual input gear inertia. Indexing of inertias and mass to the motion of a single part is common in multibody analysis of geared systems.

8. System Damping. A torque applied to the gear output in proportion to the angular speed of the gear, opposing the direction of motion.

9. System Friction. A constant torque applied to the gear output opposing its direction of motion. It requires a reference angle representing about one third of the width of the hysteresis loop observed when the direction of travel is reversed.

10. Steer Compliance. In addition to the compliance of the suspension system, the steering system contributes some compliance. Suspension system compliances are typically measured with opposed-force tests, to avoid steering system effects. A second measurement using parallel forces includes both steering and suspension compliance. The suspension effect is subtracted from this total to obtain the steering system compliance. It is expressed as the steer of each wheel due to the sum of the kingpin moments.
11. Kinematics. This is a table of steer of the road wheel as a function of Pitman Arm rotation. It includes the geometry of the tie rods, steering arm, and drag link.
12. (Optional) Steer angle limit stops. When the steering control is by torque, if the input torque exceeds the reaction torque unrealistic steer angles can be reached. This may cause instability or just incorrect results. Imposing torsional springs to limit travel prevents this. When steer is controlled by input angle, they are unnecessary and should be disabled by setting to zero.

Not shown in this schematic but included in the model (see screen description for more), are

1. Axle wrap compliance. A torque applied to the axle from, for example, braking, may cause a compliant rotation in the side view (Y rotation), known as *axle wrap*. A coefficient describes the amount of wrap per unit of applied torque.
2. A ratio describing steer of the system, per degree of wrap. Axel wrap causes the angle of the drag link to change, so its motion through an arc steers the system.
3. Wheel steer with axle jounce. Just as wrap changes the angle of the drag link, axle jounce does also. A coefficient describes this relationship.

Manual Rack and Pinion

Figure 5 shows a schematic of a Manual (e.g., no assist) Rack and Pinion steering system. This is the simplest system available. If your simulations don't require detailed information about steer torque and deflection, it is recommended you use one of the manual steering options.

The system definition and its equations are the same for both left- and right- hand drive systems.

The Manual Rack and Pinion system elements are:

1. Steering Column Inertia. This consists of the column components from the steering wheel to the pinion, but not including the pinion.
2. Steering Column Friction. A constant torque due to rotating friction that always opposes the direction of rotation. It requires a reference angle representing about one third of the width of the hysteresis loop observed when the direction of travel is reversed.
3. Steering Column Damping. A torque in proportion to the steering column angular rate, opposing the direction of rotation.

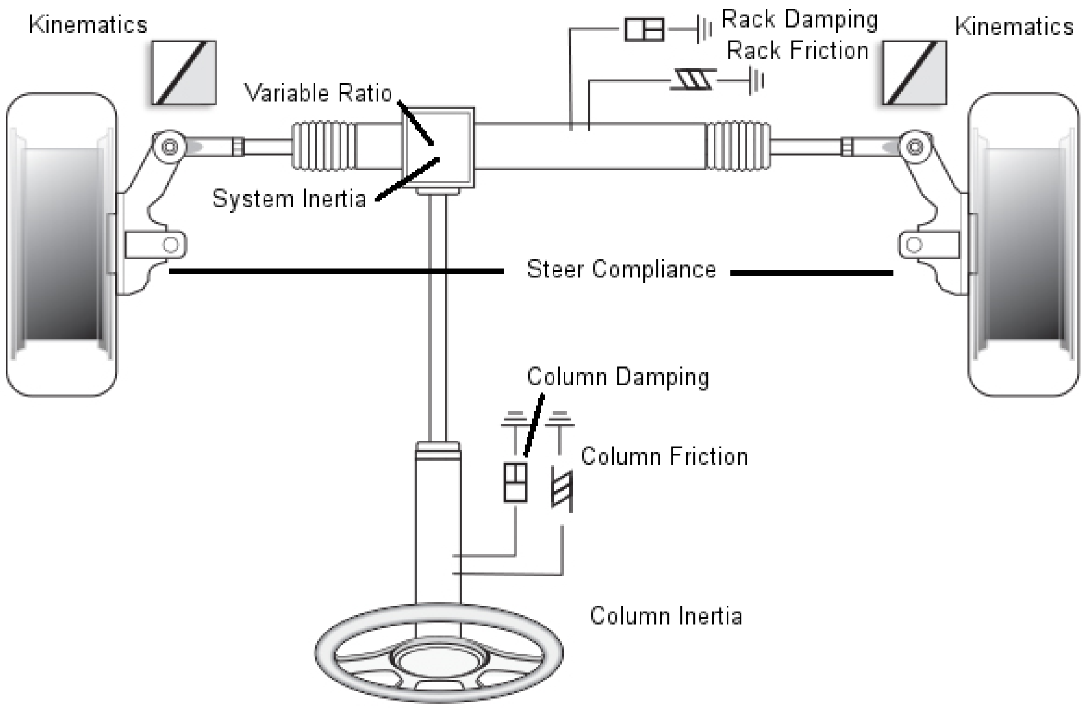


Figure 5. Manual Rack and Pinion.

4. Steering gear ratio. This is most often expressed as a "C-factor" for single-ratio rack assemblies. The C-Factor is the lateral displacement of the rack in one full turn of the pinion. The relationship is internally represented by a table (configurable function) whose input is degrees of pinion rotation and output is millimeters of rack translation. In a manual system, the pinion angle and steering wheel angle (possibly modified by intermediate shaft kinematics) are the same.

5. (Optional) Intermediate shaft kinematics. The geometry of the intermediate shaft and its joints causes the output angle to lead or lag the input rotation, expressed here as a table of output rotation versus input rotation.

6. System Inertia. Includes the effect of the mass of the rack, tie rods, etc. expressed as a rotational inertia indexed to the pinion speed, plus the actual pinion inertia. Indexing of inertias and mass to the motion of a single part is common in multibody analysis of geared systems. It may be helpful to think of it as the mass of the various components at a point on the pitch radius of the pinion.

7. Rack Damping. A force applied to the rack in proportion to the translational speed of the rack, opposing the direction of motion.

8. Rack Friction. A constant force applied to the rack opposing its direction of motion. It requires a reference length representing about one third of the width of the hysteresis loop observed when the direction is reversed.

9. Steering Compliance. In addition to the compliance of the suspension system, the steering system contributes some compliance. Suspension system compliances are typically measured with opposed-force tests, to avoid steering system effects. A second

measurement using parallel forces includes both steering and suspension compliance. The suspension effect is subtracted from this total to obtain the steering system compliance. It is expressed as the steer of each wheel due to the sum of the kingpin moments.

10. Kinematics. This is a table of steer of the road wheel as a function of rack translation. It includes the geometry of the tie rods and steering arm.
11. (Optional) Steer angle limit stops. When the steering control is by torque, if the input torque exceeds the reaction torque unrealistic steer angles can be reached. This may cause instability or just incorrect results. Imposing torsional springs to limit travel prevents this. When steer is controlled by input angle, they are unnecessary and should be disabled by setting to zero.

In this system, all steering effects are kinematically related. If steering is controlled by setting the steer angle, as by open loop control or by the closed loop path follower ("driver model"), the rack position is a function of the steer angle and the wheel positions are functions of the rack position. There is no "degree of freedom" because all motions are constrained.

If the system is controlled by torque applied to the steering wheel, the motions are still kinematically related, but the motions result from integrating an equation. Thus, in torque control, manual steering adds one degree of freedom to the vehicle model.

Manual Recirculating Ball

Figure 6 shows a schematic of a Manual (e.g., no assist) Recirculating Ball steering system. Although we refer to this system as "recirculating ball", it just means the input is rotation and the output is rotation. Other types of gears such as "worm and sector" or "worm and roller" also use this system. If your simulations don't require detailed information about steer torque and deflection, this system or its counterpart Manual Rack and Pinion is recommended.

The system definition and its equations are the same for both left- and right- hand drive systems.

The Manual Recirculating Ball system elements are:

1. Steering Column Inertia. This consists of the column components from the wheel to the input gear, but not including the input gear itself.
2. Steering Column Friction. A constant torque due to rotating friction that always opposes the direction of rotation. It requires a reference angle representing about one third of the width of the hysteresis loop observed when the direction of travel is reversed.
3. Steering Column Damping. A torque in proportion to the steering column angular rate, opposing the direction of rotation.
4. Steering gear ratio. This is the input (steering wheel) angle per degree of output (Pitman arm) angle. The relationship is internally represented by a table (configurable function) whose input is degrees of steering input gear rotation and output is degrees of Pitman arm rotation. In a manual system, the input gear angle and steering wheel angle (possibly modified by intermediate shaft kinematics) are the same.

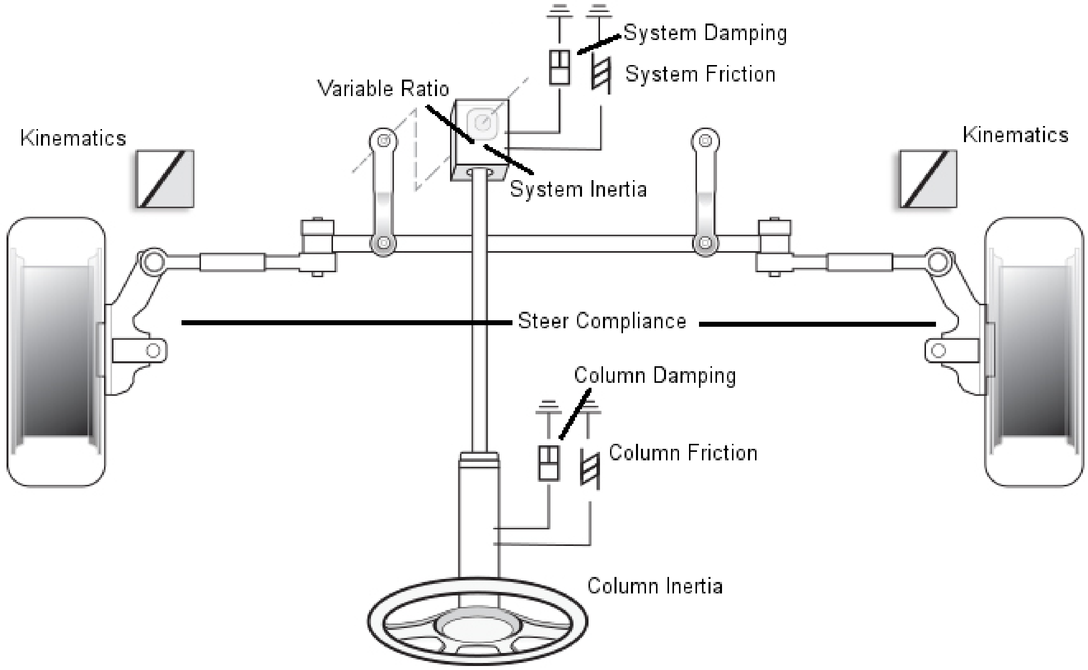


Figure 6. Manual Recirculating Ball.

5. (Optional) Intermediate shaft kinematics. The geometry of the intermediate shaft and its joints causes the output angle to lead or lag the input rotation, expressed here as a table of output rotation versus input rotation.

6. System Inertia. Includes the effect of the mass and inertia of the relay rod, tie rods, Pitman arm, idler arm, etc. expressed as a rotational inertia indexed to the input speed, plus the actual input gear inertia. Indexing of inertias and mass to the motion of a single part is common in multibody analysis of geared systems.

7. System Damping. A torque applied to the gear output in proportion to the angular speed of the gear, opposing the direction of motion.

8. System Friction. A constant torque applied to the rack opposing its direction of motion. It requires a reference length representing about one third of the width of the hysteresis loop observed when the direction of travel is reversed.

9. Steering Compliance. In addition to the compliance of the suspension system, the steering system contributes some compliance. Suspension system compliances are typically measured with opposed-force tests, to avoid steering system effects. A second measurement using parallel forces includes both steering and suspension compliance. The suspension effect is subtracted from this total to obtain the steering system compliance. It is expressed as the steer of each wheel due to the sum of the kingpin moments.

10. Kinematics. This is a table of steer of the road wheel as a function of rack translation. It includes the geometry of the tie rods and steering arm.

11. (Optional) Steer angle limit stops. When the steering control is by torque, if the input torque exceeds the reaction torque unrealistic steer angles can be reached. This may cause

instability or just incorrect results. Imposing torsional springs to limit travel prevents this. When steer is controlled by input angle, they are unnecessary and should be disabled by setting to zero.

In this system, all steering effects are kinematically related. If steering is controlled by setting the steer angle, as by open loop control or by the closed loop path follower ("driver model"), the Pitman position is a function of the steer angle and the wheel positions are functions of the Pitman arm position. There is no "degree of freedom" because all motions are constrained.

If the system is controlled by torque applied to the steering wheel, the motions are still kinematically related, but the motions result from integrating an equation. Thus, in torque control, manual steering adds one degree of freedom to the vehicle model.

Power Assisted Asymmetric Steer

Figure 7 shows a schematic of a Power Assisted Asymmetric steering system. These systems are typical of heavy truck steering. Due to the lateral tie rod connecting the two wheels, they are used exclusively on solid axles. Either the left or right wheel may receive primary control, but for the sake of brevity only left wheel control is shown. If your simulations don't require detailed information about steer torque and deflection, it is recommended you use one of the manual steering options.

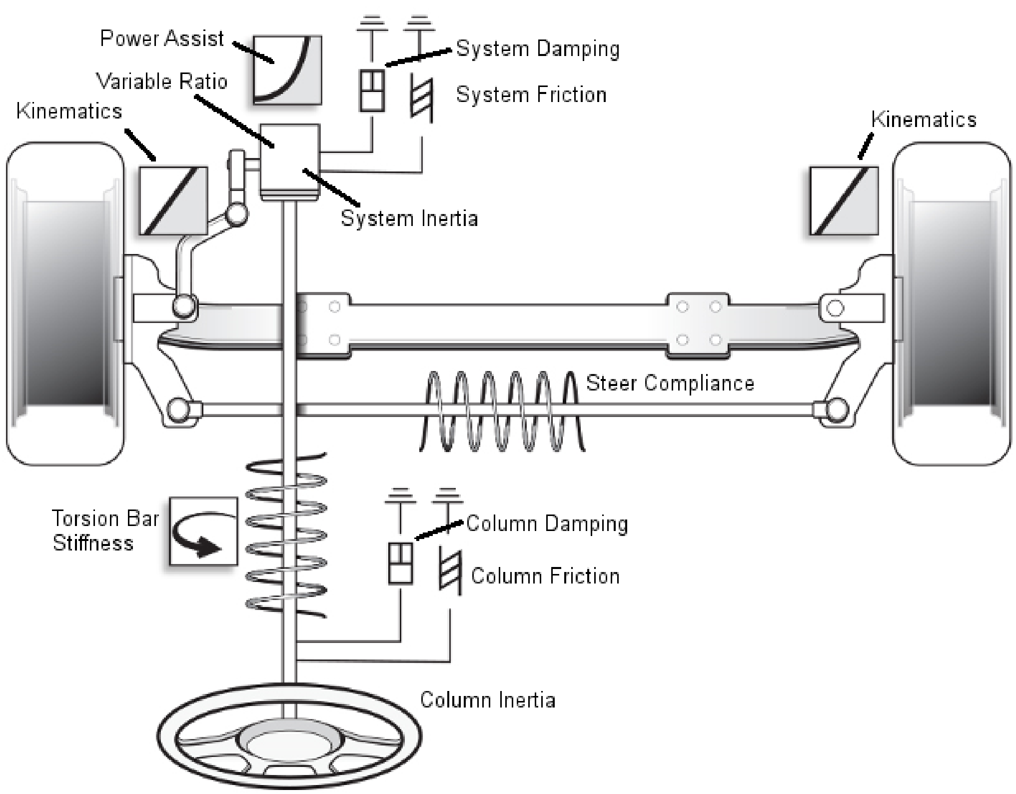


Figure 7. Power Asymmetric Steer.

The system definition and its equations are the same for both left- and right- hand drive systems.

The Power Assisted Asymmetric system elements are:

1. Steering Column Inertia. This consists of the column components from the steering wheel to the pinion, but not including the pinion.
2. Steering Column Friction. A constant torque due to rotating friction that always opposes the direction of rotation. It requires a reference angle representing about one third of the width of the hysteresis loop observed when the direction of travel is reversed.
3. Steering Column Damping. A torque in proportion to the steering column angular rate, opposing the direction of rotation.
4. Torsion Bar Stiffness. The torsion bar is a torsional spring between the steering column and the input side of the steering gearbox. It serves as a torque sensor by allowing relative rotation of the column and the input gear. The rotation might be measured electronically or optically, or it might control the position of a hydraulic valve in hydraulic power assist systems. Because it is implemented as a spring, the angle of the input gear and the angle of the steering column are not identical as they are in the Manual system. The motion of the gear is calculated by the integration of a differential equation involving all the forces applied to the rack and the System Inertia.
5. Steering gear ratio. This is the input (steering wheel) angle per degree of output (Pitman arm) angle. The relationship is internally represented by a table (configurable function) whose input is degrees of steering input gear rotation and output is degrees of Pitman arm rotation. In a manual system, the input gear angle and steering wheel angle (possibly modified by intermediate shaft kinematics) are the same.
6. (Optional) Intermediate shaft kinematics. The geometry of the intermediate shaft and its joints causes the output angle to lead or lag the input rotation, expressed here as a table of output rotation versus input rotation. When the assist is applied to the column, the output angle of the torsion bar is the input to the intermediate shaft, and the output of the intermediate shaft is input to the steering gear. When the assist is applied to the gear, output angle of the intermediate shaft is the input to the torsion bar, and the output of the torsion bar is input to the steering gear.
7. Steering Column Compliance. In manual (no power assist) systems, the steering column typically exhibits some angular compliance when torque is applied. In power assisted systems this represents compliance in addition to that of the torsion bar, from components such as joints.
8. System Inertia. Includes the effect of the mass and inertia of the relay rod, tie rods, Pitman arm, idler arm, etc. expressed as a rotational inertia indexed to the input speed, plus the actual input gear inertia. Indexing of inertias and mass to the motion of a single part is common in multibody analysis of geared systems.
9. Power Assist (Boost). This is implemented as a torque applied to the output gear (“gear assist”) or a torque applied to the input gear (“column assist”), as specified by a pull-down control for the selection of the system type. The boost level is from a table (configurable function) with Torsion Bar torque as its input and Boost Torque as its output. To avoid numerical stiffness in the math model, and to simulate the hydraulic or electrical delay in

boost systems, a time constant is employed. The time constant is applied to the boost torque.

10. System Damping. A torque applied to the gear output in proportion to the angular speed of the gear, opposing the direction of motion.
11. System Friction. A constant torque applied to the gear output opposing its direction of motion. It requires a reference angle representing about one third of the width of the hysteresis loop observed when the direction of travel is reversed.
12. Steer Compliance. In addition to the compliance of the suspension system, the steering system contributes some compliance. Suspension system compliances are typically measured with opposed-force tests, to avoid steering system effects. A second measurement using parallel forces includes both steering and suspension compliance. The suspension effect is subtracted from this total to obtain the steering system compliance. It is expressed as the steer of each wheel due to the sum of the kingpin moments.
13. Kinematics. This is a table of steer of the road wheel as a function of Pitman Arm rotation. It includes the geometry of the tie rods, steering arm, and drag link.
14. (Optional) Steer angle limit stops. When the steering control is by torque, if the input torque exceeds the reaction torque unrealistic steer angles can be reached. This may cause instability or just incorrect results. Imposing torsional springs to limit travel prevents this. When steer is controlled by input angle, they are unnecessary and should be disabled by setting to zero.

Not shown in this schematic but included in the model (see screen description for more), are

1. Axle wrap compliance. A torque applied to the axle from, for example, braking, may cause a compliant rotation in the side view (Y rotation), known as *axle wrap*. A coefficient describes the amount of wrap per unit of applied torque.

2. A ratio describing steer of the system, per degree of wrap. Axel wrap causes the angle of the drag link to change, so its motion through an arc steers the system.

3. Wheel steer with axle jounce. Just as wrap changes the angle of the drag link, axle jounce does also. A coefficient describes this relationship.

In this system, the position of the column and position of the steering input gear are not the same, because the torsion bar deflects under load. If steering is controlled by setting the steer angle, as by open loop control or by the closed loop path follower (“driver model”), the column has no degree of freedom because it is constrained, so changes to the column inertia have no effect.

The Pitman arm position results from integration of an equation involving all the torques applied to the output side of the gear including the torsion bar torque, assist torque, damping, friction, and tie rod forces expressed as a torque at the Pitman arm. Thus, the system from the input gear to the wheels always adds one degree of freedom to the model. The wheel steer angles are kinematically linked to the Pitman arm position.

If the system is controlled by torque applied to the steering wheel, the motion of the steering wheel results from integrating an equation. Thus, in torque control, power steering adds two degrees of freedom to the vehicle model.

Power Assisted Rack and Pinion

Figure 8 shows a schematic of a Power Rack and Pinion steering system. Rack and pinion steering with assist applied either to the rack or to the column is the most common system in passenger cars and light trucks today. However, power assist adds some complexity to the steering system specifications and an additional dynamical degree of freedom, so if your simulation doesn't require detailed data about steering torque and angles, we recommend you use one of the Manual steering options.

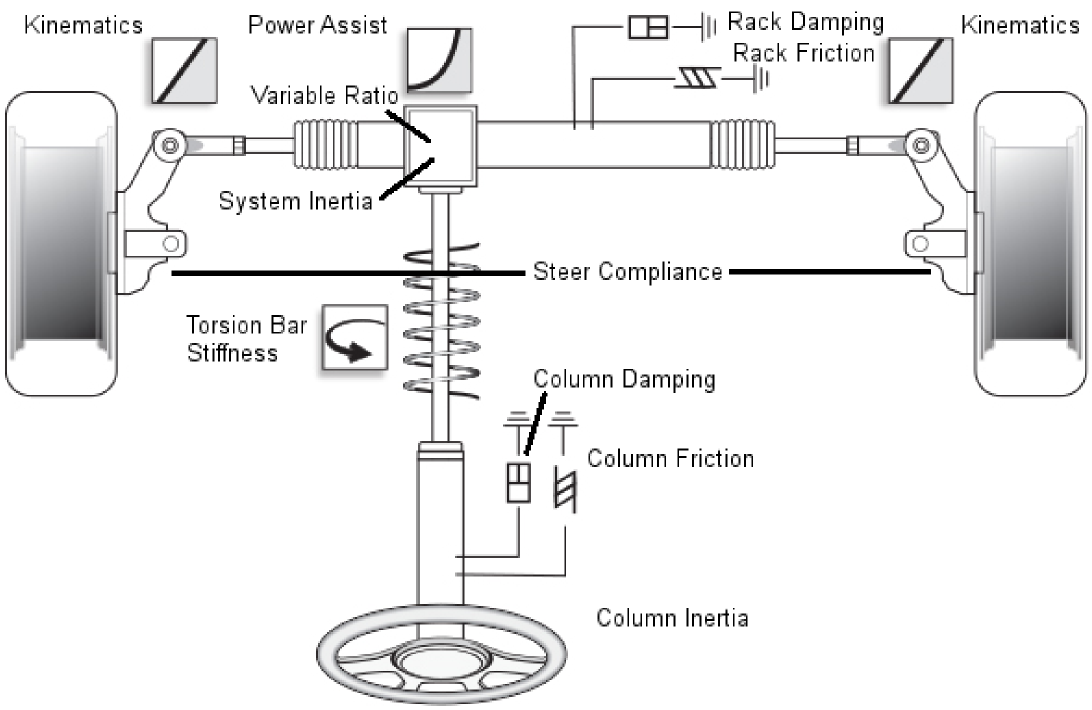


Figure 8. Power Rack and Pinion.

The Power Assisted Rack and Pinion system elements are:

1. Steering Column Inertia. This consists of the column components from the wheel to the pinion, but not including the pinion.
2. Steering Column Friction. A constant torque due to rotating friction that always opposes the direction of rotation. It requires a reference angle representing about one third of the width of the hysteresis loop observed when the direction of travel is reversed.
3. Steering Column Damping. A torque in proportion to the steering column angular rate, opposing the direction of rotation.
4. Torsion Bar Stiffness. The torsion bar is a torsional spring between the steering column and the input side of the pinion. It serves as a torque sensor by allowing relative rotation

of the column and the pinion. The rotation might be measured electronically or optically, or it might control the position of a hydraulic valve in hydraulic power assist systems. Because it is implemented as a spring, the angle of the pinon and the angle of the steering column are not identical as they are in the Manual system. The motion of the rack is calculated by the integration of a differential equation involving all the forces applied to the rack and the System Inertia.

5. Steering gear ratio. This is most often expressed as a "C-factor" for single-ratio rack assemblies. The C-Factor is the lateral displacement of the rack in one full turn of the pinion. The relationship is internally represented by a table (configurable function) whose input is degrees of pinion rotation and output is millimeters of rack translation. In a manual system, the pinion angle and steering wheel angle (possibly modified by intermediate shaft kinematics) are the same. In a power assisted system, the pinion angle results from the rack motion calculated by the integration of a differential equation involving all the forces applied to the rack and the System Inertia.

6. (Optional) Intermediate shaft kinematics. The geometry of the intermediate shaft and its joints causes the output angle to lead or lag the input rotation, expressed here as a table of output rotation versus input rotation. When the assist is applied to the column, the output angle of the torsion bar is the input to the intermediate shaft, and the output of the intermediate shaft is input to the pinion. When the assist is applied to the rack, output angle of the intermediate shaft is the input to the torsion bar, and the output of the torsion bar is input to the pinion.

7. System Inertia. Includes the effect of the mass of the rack, tie rods, etc. expressed as a rotational inertia indexed to the pinion speed, plus the actual pinion inertia. Indexing of inertias and mass to the motion of a single part is common in multibody analysis of geared systems. It may be helpful to think of it as the mass of the various components at a point on the pitch radius of the pinion.

8. Power Assist (Boost). This is implemented as a force applied to the rack ("rack assist") or a torque applied to the pinion ("column assist"), as specified by a pull-down control for the selection of the system type. The boost level is from a table (configurable function) with Torsion Bar torque as its input and Boost Force (rack assist) or Boost Torque (column assist) as its output. To avoid numerical stiffness in the math model, and to simulate the hydraulic or electrical delay in boost systems, a time constant is employed. The time constant is applied to the boost force or torque.

9. Rack Damping. A force applied to the rack in proportion to the translational speed of the rack, opposing the direction of motion.

10. Rack Friction. A constant force applied to the rack opposing its direction of motion. It requires a reference length representing one third of the width of the hysteresis loop observed when the direction is reversed.

11. Steering Compliance. In addition to the compliance of the suspension system, the steering system contributes some compliance. Suspension system compliances are typically measured with opposed-force tests, to avoid steering system effects. A second measurement using parallel forces includes both steering and suspension compliance. The

suspension effect is subtracted from this total to obtain the steering system compliance. It is expressed as the steer of each wheel due to the sum of the kingpin moments.

12. Kinematics. This is a table of steer of the road wheel as a function of rack translation. It includes the geometry of the tie rods and steering arm.

13. (Optional) Steer angle limit stops. When the steering control is by torque, if the input torque exceeds the reaction torque unrealistic steer angles can be reached. This may cause instability or just incorrect results. Imposing torsional springs to limit travel prevents this. When steer is controlled by input angle, they are unnecessary and should be disabled by setting to zero.

In this system, the position of the column and position of the pinion are not the same, because the torsion bar deflects under load. If steering is controlled by setting the steer angle, as by open loop control or by the closed loop path follower ("driver model"), the column has no degree of freedom because it is constrained, so changes to the column inertia have no effect.

The rack position results from integration of an equation involving all the forces applied to the rack including the torsion bar torque, assist force or torque, damping, friction, and tie rod forces. Thus, the system from the pinion to the wheels always adds one degree of freedom to the model. The wheel steer angles are kinematically linked to the rack position.

If the system is controlled by torque applied to the steering wheel, the motion of the steering wheel results from integrating an equation. Thus, in torque control, power steering adds two degrees of freedom to the vehicle model.

Power Assisted Recirculating Ball

Figure 9 shows a schematic of a Power Recirculating Ball steering system. Steering power assist is applied either to the rack or to the column. However, power assist adds some complexity to the steering system specifications and an additional dynamical degree of freedom, so if your simulation doesn't require detailed data about steering torque and angles, we recommend you use one of the Manual steering options.

The Power Assisted Recirculating Ball system elements are:

1. Steering Column Inertia. This consists of the column components from the wheel to the pinion, but not including the pinion.

2. Steering Column Friction. A constant torque due to rotating friction that always opposes the direction of rotation. It requires a reference angle representing about one third of the width of the hysteresis loop observed when the direction of travel is reversed.

3. Steering Column Damping. A torque in proportion to the steering column angular rate, opposing the direction of rotation.

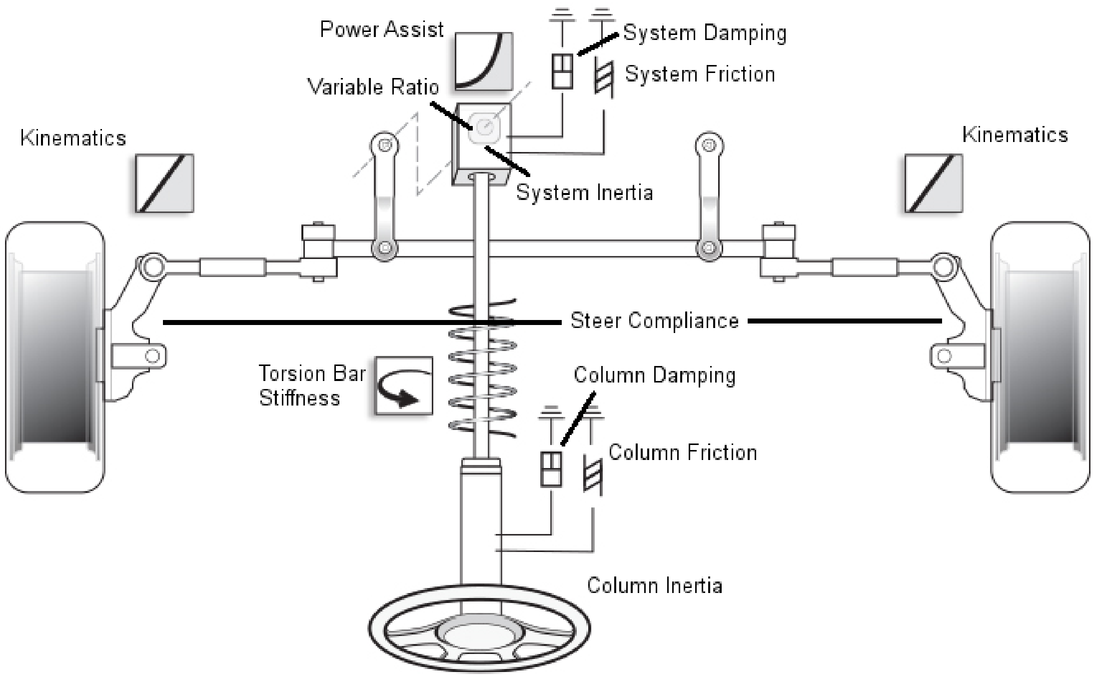


Figure 9. Power Recirculating Ball.

4. Torsion Bar Stiffness. The torsion bar is a torsional spring between the steering column and the input side of the gear. It serves as a torque sensor by allowing relative rotation of the column and the gear. The rotation might be measured electronically or optically, or it might control the position of a hydraulic valve in hydraulic power assist systems. Because it is implemented as a spring, the angle of the steering input gear and the angle of the steering column are not identical as they are in the Manual system. The motion of the output gear is calculated by the integration of a differential equation involving all the forces applied to the gear and linkage and the System Inertia.

5. Steering gear ratio. This is the input (steering wheel) angle per degree of output (Pitman arm) angle. The relationship is internally represented by a table (configurable function) whose input is degrees of steering input gear rotation and output is degrees of Pitman arm rotation. In a manual system, the input gear angle and steering wheel angle (possibly modified by intermediate shaft kinematics) are the same.

6. (Optional) Intermediate shaft kinematics. The geometry of the intermediate shaft and its joints causes the output angle to lead or lag the input rotation, expressed here as a table of output rotation versus input rotation. When the assist is applied to the column, the output angle of the torsion bar is the input to the intermediate shaft, and the output of the intermediate shaft is input to the steering gear. When the assist is applied to the gear, output angle of the intermediate shaft is the input to the torsion bar, and the output of the torsion bar is input to the steering gear.

7. System Inertia. Includes the effect of the mass and inertia of the relay rod, tie rods, Pitman arm, idler arm, etc. expressed as a rotational inertia indexed to the input speed, plus the

actual input gear inertia. Indexing of inertias and mass to the motion of a single part is common in multibody analysis of geared systems.

8. Power Assist (Boost). This is implemented as a torque applied to the output gear ("gear assist") or a torque applied to the input gear ("column assist"), as specified by a pull-down control for the selection of the system type. The boost level is from a table (configurable function) with Torsion Bar torque as its input and Boost Torque as its output. To avoid numerical stiffness in the math model, and to simulate the hydraulic or electrical delay in boost systems, a time constant is employed. The time constant is applied to the boost torque.

9. System Damping. A torque applied to the gear output in proportion to the angular speed of the gear, opposing the direction of motion.

10. System Friction. A constant torque applied to the rack opposing its direction of motion. It requires a reference length representing one third of the width of the hysteresis loop observed when the direction is reversed.

11. Steering Compliance. In addition to the compliance of the suspension system, the steering system contributes some compliance. Suspension system compliances are typically measured with opposed-force tests, to avoid steering system effects. A second measurement using parallel forces includes both steering and suspension compliance. The suspension effect is subtracted from this total to obtain the steering system compliance. It is expressed as the steer of each wheel due to the sum of the kingpin moments.

12. Kinematics. This is a table of steer of the road wheel as a function of rack translation. It includes the geometry of the tie rods and steering arm.

13. (Optional) Steer angle limit stops. When the steering control is by torque, if the input torque exceeds the reaction torque unrealistic steer angles can be reached. This may cause instability or just incorrect results. Imposing torsional springs to limit travel prevents this. When steer is controlled by input angle, they are unnecessary and should be disabled by setting to zero.

In this system, the position of the column and position of the steering input gear are not the same, because the torsion bar deflects under load. If steering is controlled by setting the steer angle, as by open loop control or by the closed loop path follower ("driver model"), the column has no degree of freedom because it is constrained, so changes to the column inertia have no effect.

The Pitman arm position results from integration of an equation involving all the torques applied to the output side of the gear including the torsion bar torque, assist torque, damping, friction, and tie rod forces expressed as a torque at the Pitman arm. Thus, the system from the input gear to the wheels always adds one degree of freedom to the model. The wheel steer angles are kinematically linked to the Pitman arm position.

If the system is controlled by torque applied to the steering wheel, the motion of the steering wheel results from integrating an equation. Thus, in torque control, power steering adds two degrees of freedom to the vehicle model.

Key Properties of the Models

In this section, refer also to the schematic sketches of the previous section and to the **Steering System Screen** and **Steering Column and Assist Screen** sections that follow.

Degrees of Freedom in the Models

Users sometimes inquire about the number of degrees of freedom (DOF's) in the steering models. A degree of freedom exists when the position of something at each timestep results from the integration of an Ordinary Differential Equation (ODE) for the body's acceleration to obtain its velocity and integration of its velocity to obtain its position.

When motion of a model element is defined by something like a table describing its position at any point in time (like steering wheel angle as a function of time) or calculated by means other than integration of ODE's (like the Closed Loop Steering Controller or "Driver Model") determining a steer angle, no degree of freedom exists for that motion. Rather, it is determined by algebraic relationships. In these situations, the motion is said to be "constrained".

When motion of something is constrained, its acceleration is unknown, and its speed can only be estimated by using backwards difference calculations. This means the properties of the thing that might influence acceleration (most notably inertia or mass) have no role in the calculation of the motion, and hence no effect on it.

The TruckSim steering system may have zero, one or two degrees of freedom, depending on model specifications and means of control.

Zero Degrees of Freedom

A manual steering system controlled by steering wheel angle adds zero degrees of freedom to the model. All the parts are linked by algebraic constraints, and the steering command defines the position at each time step.

One Degree of Freedom

A manual steering system controlled by steering torque input adds one DOF. All components are algebraically linked to the steering column motion, so motion of the column, rack or gear, and steer of the wheels results from integration of a complex expression involving the inertias and masses of all these parts, and all forces (damping, hysteresis, tire forces, etc.) applied to the parts in the system.

A power assisted steering system controlled by steering wheel angle also adds one DOF to the model. In power assisted systems, the column motion and rack (or gear) motion are not algebraically constrained. Instead, a spring (the torsion bar) is introduced between the column and the steering gear input. The motion of all parts below the torsion bar (rack or gear, steer of wheels) results from integrating complex expressions involving the masses and inertias of all these parts and all the forces applied to them. The steering column, however, is constrained to have a specific steer angle, so its acceleration is not known, and its inertia has no effect. Feedback torque to steering wheel includes the torque at the torsion bar (resulting from angular deflection of the input gear), the column hysteresis, and the column damping (using a backwards difference to obtain an estimate of the angular rate), but no effect of the angular acceleration, which is unknown. In these cases, we say the input (driver model or open loop steer command) is capable of infinite torque, as it simply positions the wheel from time step to time step.

Two Degrees of Freedom

A power assisted steering system controlled by steer torque adds a further DOF to the system, for a total of two. In this case, the angular acceleration of the column is also obtained from integration, as is the angular rate.

Anytime a DOF is added to the model there is the potential of instability if parameters for inertias and forces or things affecting forces (like tire relaxation length, power assist boost time constant, etc.) are poorly chosen. For this reason, we recommend that simulations not requiring detailed information about steer torques and angles use one of the manual steer options. The deflection of the torsion bar does affect the required steer input to obtain a given steer output, so things like the vehicle's understeer gradient reflect this.

Calculation of Steering Torque and Tie Rod Loads

Steering Wheel Torque

As described above, steering wheel torque results from one of two possible sources. In the case of control by steering torque, the input torque is known because it is specified in the simulation data.

In the case of control by angle, steering wheel torque is summed from several effects.

The power assisted cases are simpler than the manual cases. Column torque is the sum of the torsion bar torque, column damping torque, and hysteresis torque. (Recall that when angle is controlled, the angular acceleration is unknown, so column inertia has no effect.)

In manual steer cases the calculation is more involved. Here, there is no torsion bar so input to the steering gear is derived by summing all the forces or torques applied to the gear or rack. Keep in mind that in the manual steer case the rack or gear position is constrained (no DOF for a torsion bar) so the gear inertia has no effect. The derived steering gear torque is added to the column torques to report the steering wheel torque.

Tie Rod Forces

Summing the forces at the gear does require information about tie rod loads. In TruckSim, elements of nearly all systems, including the steering system, are defined at a system level. This means we don't have information about exact location of joints or links like tie rods. Without knowledge of tie rod geometry, and since the motion is constrained, we must infer tie rod loads from other information.

While we don't know the detailed forces at any constraint (ball joints, tie rods) we know the total motion of the steered wheel and steered suspension parts (knuckle, brake parts, etc.). Because we know its motion, mass and inertia, we can calculate the total force and moment applied to the body. Subtracting the active forces (tire forces, brakes, springs, dampers, etc.) leaves the total force and moment due to constraints. These are *reaction forces and moments*. The component of the reaction moment along the steer axis is the steer torque due to all forces and moments. (The component not along the steer axis is reacted by other constraints).

The constraint information about the wheel-end kinematics (tie rod / steering arm) implies an effective moment arm. From this moment arm and the sum of the steer moments a force can be obtained. This force is applied to the rack in the case where it is power assisted, or just used to get the total rack force in manual steer. (When steering is by a gear rather than rack, a moment due to tie rods is calculated because there is no information about the Pitman arm length).

In Asymmetric steering systems, the "tie rod loads" are the moments applied to the gear output resulting from left-side and right-side kingpin moments, fed back through the system.

Properties of the Steering Column and Steering Gear

The steering system is roughly divided into two sections: the column and the gear (including the pinion or input gear). In power steering systems, the column is connected to the gear by a torsion bar. In manual steering systems, no torsion bar is present, and the column connects directly to the input gear. See the section on **The Steering Screen** later in this document.

Steering column properties are its inertia, a damping coefficient, and friction (hysteresis) consisting of a force magnitude and a reference angle equal to about one third the width in degrees of the hysteresis loop.

Properties of the rack or gear are a system inertia, damping coefficient, and hysteresis. The inertia is listed with the column properties because it is indexed to the pinion or input gear.

The inertia represents the mass of components including the rack and tie rods, and the inertia of the pinion or input gear, and the inertia of an output gear and pitman arm. A single inertia value is used rather than individual masses or inertias for the parts. The inertia is indexed to the pinion or input gear. Indexing of properties in geared systems to a single element of the system is common in multibody modeling. One way to think of an estimate for the system inertia is to think of the mass of the rack and tie rods concentrated as a point at the pitch radius of the pinion. (Note that the "C-factor" of a rack and pinion is just the pitch circumference of the pinion). The inertia indexed to the input gear would then be the mass multiplied by the square of the pitch radius.

Beginning in TruckSim 2021.0, TruckSim can automatically calculate a suspension contribution term and add it to the user-provided system inertia value. This feature is enabled based on the setting of the parameter `OPT_I_GEAR_IN`:

- `OPT_I_GEAR_IN = 0`. The suspension contribution to steering system inertia is not calculated automatically. The user-provided value of `I_GEAR_IN` is used as-is. The user must calculate the suspension contribution themselves and include it in the specified `I_GEAR_IN`; alternatively, the user may decide to neglect the suspension contribution.
- `OPT_I_GEAR_IN = 1`. The kingpin geometry, steered unsprung mass and inertias, linkage kinematics, and steering gear kinematics are used to calculate an inertia term which represents the rotation of the steered unsprung masses around the left and right kingpin axes. This term is referenced to the steering gear input rotation and is added to the user-provided `I_GEAR_IN` value. In other words, the user-provided value is the steering system inertia not including the effect of the unsprung masses rotating about the kingpins. The total steering system inertia, consisting of the user-provided value plus the calculated value from the suspension, is output with the output variable `IstrGear`. It is also available in

the Echo file as `I_GEAR_IN_TOT`. The total steering system inertia is, in general, not constant due to the nonlinear kinematics.

Versions of TruckSim prior to 2021.0 are equivalent to setting `OPT_I_GEAR_IN` to 0 and neglecting the suspension contribution to the system inertia. Consequently, turning the suspension contribution on will cause differences in simulation results. This may require re-assessing and suitably adjusting steering system data such as damping and assist-force time constant.

One final note on steering system inertia `I_GEAR_IN`: this value is only needed for fully internal steering systems (`OPT_STEER_EXT = 0`). In all other cases, the value is ignored.

The damping and hysteresis values of the rack or gear are referenced to the output side.

Control Method and the Effects of Certain Properties

When the motion of an object is constrained, as when the input to steering is by controlling steer angle in either open- or closed-loop control, the position isn't obtained by integration of an ordinary differential equation (ODE), but simply set as a value from a lookup table, the output of the closed loop driver model, or imported from external code or VS Commands.

Without an ODE, the acceleration of the body is unknown. Effects of inertia are experienced as reactions to acceleration. So, when a body is constrained and its acceleration is not obtained for an ODE, its inertia can have no effect on motion.

This means that when steer angle is controlled rather than torque, the column inertia can have no effect. In a manual steering system with no torsion bar between the column and gear, the system inertias likewise have no effect.

In torque control, however, the various forces (input torque, damping torque, hysteresis torque, possibly torsion bar torque) are applied to the inertia to obtain acceleration. The acceleration is integrated to obtain speed and position.

Users might be tempted to enter values like zero for inertias that won't have effect in angle control but are cautioned against it. At some point you might create simulations using the same vehicle with torque control. In that event, the simulation will fail.

Steer of Multiple Axles and Steer of Trailer Axles

It is possible to steer any axle on a TruckSim vehicle, including trailer axles. By default, only the first axle on the lead unit is steered. The **Vehicle: Lead Unit** screen supports specification of steering for all other axles via pull-down controls that reveal additional fields and links to describe its properties. Trailer screens do not directly support steer, but it can be added using generic screens and miscellaneous controls.

Specifying an axle to be steered adds considerable complexity to the model, so it should only be used when necessary.

The internal steering model for an axle is enabled by setting `OPT_STEER_EXT(`*iaxle*`)` to 0 and disabled by setting it to 1. 0 is the default value for axle 1 and 1 is the default for all other axles.

If you need to create a steerable trailer, you can create a lead unit with 4-wheel steer and study the Parsfile for the steering system screen to see the added parameters and configurable functions, or you can consult Mechanical Simulation for assistance.

Note that axles other than the first axle are assumed to be servo controlled. Only the effects at the first axle contribute to driver steer torque.

Effects of Kingpin Geometry

The kingpin (steering axis) is defined by its location with respect to the wheel center, and its inclination in side view (the caster angle) and front view (the kingpin inclination angle). When the wheel is steered, the wheel and the steered portion of the suspension rotate about the kingpin axis. The combined effects of the offsets and inclination cause the center of tire contact to move through an arc about the kingpin axis intersection with the ground, cause the wheel to camber, and move the wheel center vertically with respect to the suspension. All these effects are included in the VS solvers.

The spin axis of a steered wheel is not, in general, perpendicular to the steering axis. In TruckSim, the kingpin axis is defined by geometric parameters that are set on the steering system screen. The corresponding orientation of the wheel spin axis is specified on the suspension kinematics screen, using static toe and camber angles. These describe the fixed 3D relationship between the steer axis and spin axis. Suspension kinematics and compliance properties affecting translations in X, Y, and Z apply to the kingpin axis. Suspension kinematics and compliance properties affecting camber and dive also apply to the kingpin axis. On the other hand, suspension effects involving toe apply to the wheel (whose orientation is in turn defined by its spin axis) as steered about the kingpin axis.

The tilt of the kingpin axis contributes a variable steering gain with kingpin steer angle, as measured by the rotation of the intersection of the wheel plane with the vehicle X-Y plane per unit of rotation about the steering axis (kingpin). The TruckSim steering system screen allows you to select the definition of the road wheel steer as either steer about the vehicle Z axis or steer about the kingpin. Defining steer with respect to the Z axis means the effects of this variable gain are included in the kinematic tables for road wheel steer (e.g., the steer was measured at the ground). Defining steer with respect to the kingpin means the effects of the variable gain are not included in the kinematic tables for road wheel steer (e.g., the steer was measured as the angle of rotation about the steer axis). The first option (steer measured at ground) is the default behavior in TruckSim. Note that here, “Steer measured at the ground” really means “Steer measured at the sprung mass X-Y datum plane, as it would be on a K&C test rig. It is not the angle of intersection of the wheel plane with the road, as vehicle movement and road geometry make this relationship continuously variable.

Power Steering System

If a power steering system is selected (see Figure 3) on the **Steering Column and Assist** screen, a blue link is available for a dataset that defines the power assist curves as a function of torsion bar torque and vehicle speed. A yellow field is available to define the torsion bar stiffness.

In common power steering system configurations, a torsion bar is placed between the steering column and steering input gear. Deflection of the torsion bar due to applied torque opens a valve, directing hydraulic pressure to the steering gear in the direction of the deflection. The pressure produces a force or torque to assist the steering. In some systems, deflection of the torsion bar is read optically or electronically, and this information is passed to a controller. The controller sends information to a motor, which produces boost at the rack or gear.

In each case the result is the same: A torsion bar is loaded by the input from the driver and the feedback from the steering system. The information is processed, hydraulically or electrically, to control a boost force or moment at the rack or gear. Column assist, when selected, is applied to the input gear.

Since the output of the system cannot change instantaneously in response to a change in input, a simple time constant is used to define a first-order delay in system response. The power steering boost curve screens have a data field for you to define a time constant for the boost system. The time constant reflects the time it takes for system boost to change from one steady state value to another in response to a change in torsion bar torque. It adds a dynamic effect to a power steering system. Specific guidelines for its value can't be given, as it depends on masses, inertias, boost levels, tire properties, torsion bar properties, and steering gear damping and hysteresis. Suffice it to say that if the time constant is too short the system will become stiff and the model may crash. If it is too long, the boost will lag the steering input and produce unrealistic results or stability issues. The time constant is applied to the boost force (or torque) in response to a change in torsion bar torque.

Power steering assist is typically limited to some maximum value by internal valving to prevent excessive pressures or current limits on a motor. A data field on the power steering boost curve screens is used to specify the maximum output force or torque. The default maximum is 10000 (N or N-m, depending on choice of steering gear type), a value higher than the maximum output of most systems. This allows you to choose whether to limit the maximum output by using flat-line extrapolation of the boost curves, or by specifying a maximum value. In the calculation, the applied boost is equal to the minimum of either the specified maximum or the value from the table.

Using Power Steering

Steering power assist systems add dynamics to the model. The torsion bar is a spring, the gear has mass (in the case of rack and pinion) or a moment of inertia (in the case of recirculating ball gears). The system produces a boost force or moment whose magnitude is subject to a time constant. If values for parameters and tables are poorly chosen, the system may exhibit instability, such as oscillation in steer torque or steer angles, or both.

Power assist can be applied either to the output side of the gear (rack or recirculating ball) or to the input side. When it is applied to the input side, we call it "column assist". Column assist is a torque applied to the pinion or input gear. On the output side, assist is applied as a force on the rack or a torque on the output gear. If the assist is imported from external models or VS Commands, the import variable for rack assist is `IMP_F_BOOST_EXT`, the force applied to the rack. For rack and pinion with column assist, recirculating ball with gear assist, or recirculating ball with column assist, the import variable name is `IMP_M_BOOST_EXT`. Note that while the variable names are the same, the point of application depends on the selection of steer type. Gear type is set with `OPT_RACK` and the power steering option is set with `OPT_POWER`. The gear type selection is normally handled by the **Steering System** screen.

Most users don't need to study the detailed behavior of a power steering system. Users might also be unfamiliar with these systems and have difficulty supplying appropriate data to describe them.

("Mix and Match" is seldom a good idea). For this reason, you should choose power assist only if you need the detailed behavior of the system. In a manual steer system, the torque reduction supplied by a power system can be mimicked by using the option to obtain steer torque from a lookup table, rather than calculating from the kingpin moments.

> **Note** If you use an import variable to replace the internally calculated power steering boost (`IMP_F_BOOST_EXT` or `IMP_M_BOOST_EXT`), set the power steering time constant (`TC_BOOST`) to zero if your external code handles system dynamics. If you want TruckSim to handle the dynamics (first order delay), give the time constant an appropriate non-zero value.

Kinematics

Steering system kinematic effects include fixed or variable ratio steer and tables for linkage kinematics. If variable ratio steering is selected, a link is provided to a table to define steering gear output (degrees or mm, depending on selected gear type) vs. steering gear input. In the case of manual steer, the steering gear input is equal to the steering wheel input. With power steering, the steering gear input is equal to the steering wheel input plus the torsion bar deflection. If a constant steer ratio is selected, a field appears to define the rack and pinion C factor (mm of rack displacement per pinion revolution, the pitch circumference of the pinion) or recirculating ball steering gear ratio (degrees of input gear rotation per degree of pitman arm rotation.)

The steering gear is connected to the steering knuckle by linkage (tie rods, for example) that modifies the steering gear output. Tables of road wheel steer per unit of steering gear output account for these effects, such as Ackerman steer.

Compliance

Compliance in the steering system is assumed to be due to the total moment about the kingpin axes of the wheels. The moments are produced by vertical load, the tire forces and aligning moment, together with the kingpin geometry. The total moment is multiplied by a nonlinear compliance function to determine the compliance steer of both wheels in a suspension. Because both wheels are driven by the same steering system, the steering system compliance steer is the same for both wheels.

Vertical tire force causes a moment about the kingpin axis. If the left and right vertical forces are not the same, such as when the chassis rolls in a turn, a net moment is applied to the steering system, possibly resulting in some compliance steer.

Speed-Sensitive Low-Speed Steer Torque (Parking Torque)

At zero speed, steering a tire requires a combination of scuffing and rolling, depending on the scrub radius (the lateral offset between the tire contact center and the intersection of the steering axis with the ground). The resistance caused by this scuffing adds a torque to the kingpin moment, increasing the steering effort at low speeds.

If you use a tire model that calculates the effects of low speed turn slip, you should set this property to zero.

These properties are described in a table on the **Steering: Parking Torque** screen.

The magnitude of this torque depends on many factors, including tire properties, steering system geometry, and static alignment. The TruckSim tire models are not designed to predict this performance, and tire data for pure turning about the contact patch center without rolling is rarely measured. Still, some applications such as hardware-in-the-loop steering test systems and driving simulators need realistic low speed steering torques.

Low speed steering torque is included as an empirically determined property of the vehicle, tires, and road. You define it as a function of speed to give realistic steering system loads at zero or very low speed, and to eliminate the effects of scuff as speed increases and behavior becomes dominated by rolling. The effect is scaled to account for the road coefficient of friction.

When the direction of steering is reversed, the observed torque does not jump instantly from one limit to the other—it takes a certain amount of steer to make the transition. A parameter called beta defines the rate at which the steering system makes the transition. Beta is sometimes called a spatial time constant, appearing in equations the same as a time constant would in first-order differential equations. However, instead of having units of time, it has units of angular deflection. Beta is about 1/3 of the angle needed to travel through 95% of the change in torque from one limit to the other. For example, if it takes 1.5° to cover 95% of the torque hysteresis, then Beta should be 0.5°.

Modified or External Steer Models (Simulink, VS Commands, etc.)

Advanced users may modify the behavior of the steering or replace all or part of the steering system with models defined externally. Typically, this is done using Simulink or VS Commands, though use of the API makes many other replacement methods possible.

The math models include many import variables that can be used to modify or replace portions of the internal model. Table 2 lists the import variables for the steering controls and Table 3 lists the Imports used for steering the wheels on axle 1. Similar variables also exist for the rear axle with suffixes other steered axles (`_L(`*`iaxle`*`)` and `_R(`*`iaxle`*`)`).

Table 2. Import variables for steering system top-level controls.

Import Keyword	Description
`IMP_DSTEER_SW`	Steering wheel angular rate
`IMP_F_BOOST_EXT`	Steering rack boost force (applies to internal steer model only)
`IMP_M_BOOST_EXT`	Steering gear boost torque (applies to internal steer model only)
`IMP_M_TBAR_EXT`	Steering column reaction torque from external model
`IMP_STEER_SW`	Steering wheel angle
`IMP_STEER_T_IN`	Steering input torque

Table 3. Import variables for steering system for axle 1.

Import Keyword	Description
IMP_DSTEER_CON_1	Steering gear angular rate for axle 1 from external model
IMP_DSTEER_CON_L1 IMP_DSTEER_CON_R1	Steering gear angular rate for wheels L1 and R1 from external model
IMP_DSTEER_L1 IMP_DSTEER_R1	Road wheel L1 and R1 steer angular rate due to the steering system (NOT ride/roll steer), from external model
IMP_DSTEER_RACK_CON_1	Steering rack speed for axle 1 from external model
IMP_DSTEER_RACK_CON_L1 IMP_DSTEER_RACK_CON_R1	Steering rack speed for wheels L1 and R1 from external model
IMP_F_TIEROD_L1 IMP_F_TIEROD_R1	Force on rack at tie rods for wheels L1 and R1 from external model
IMP_M_KP_L1 IMP_M_KP_R1	Additional kingpin torques reacted at sprung mass
IMP_M_TIEROD_L1 IMP_M_TIEROD_R1	Moment at Pitman arm due to load in tie rods for wheels L1 and R1 from external model
IMP_R_STR_EXT_L1 IMP_R_STR_EXT_R1	Overall steer ratio for wheel L1 with external steer model, used by the closed loop steering controller (driver model)
IMP_STEER_CON_1	Steering gear angle for axle 1 from external model
IMP_STEER_CON_L1 IMP_STEER_CON_R1	Steering gear output angle for wheels L1 and R1 (input to nonlinear steering kinematics table) from external model
IMP_STEER_L1 IMP_STEER_R1	Road wheels L1 and R1 steer angle due to the steering system, (NOT ride/roll steer) from external model
IMP_STEER_RACK_CON_1	Steering rack position for axle 1 (input to nonlinear steering kinematics table) from external model
IMP_STEER_RACK_CON_L1 IMP_STEER_RACK_CON_R1	Steering rack position for wheels L1 and R1 (input to nonlinear steering kinematics table) from external model

Advanced users may use many combinations of these import variables to modify or replace portions of the steering system model. In addition, parameters are provided for each axle to support three options to replace sections of the model. The parameters are `OPT_STEER_EXT(`*iaxle*`)`. Valid values of `OPT_STEER_EXT` are the integers 0 through 4.

Keep in mind that, when `OPT_STEER_EXT` is set to 2, 3, or 4, a specific part or parts of the steering system are to be replaced, and the internal code to describe that part of the system is bypassed. That is, TruckSim has no information about that part of the system, so a user must provide all the information normally calculated internally for that system.

Note All the steering system import variables support all the available modes for imports (ADD, REPLACE, MULTIPLY). However, when OPT_STEER_EXT is set to replace all or part of the internal system, the use of MULTIPLY for the variables representing the effects of the replaced components doesn't make sense because there is no internal counterpart. (Effectively, the import is multiplied by zero, thus having no effect.) In these cases, only ADD or REPLACE should be used. See the following sections for details on the specific imports required in each case.

Using the Import Variables to Modify Steering Rack or Gear Behavior

As noted above, the steering system import variables support all the optional modes for imports (ADD, REPLACE, MULTIPLY). The imports that represent rack or gear motion need some special considerations.

Table 4. Import variables for wheel steer control for axle 1.

Import Keyword	Description
IMP_DSTEER_CON_1	Steering gear angular rate axle 1 from external model
IMP_DSTEER_RACK_CON_1	Steering rack speed for axle 1 from external model
IMP_STEER_CON_1	Steering gear output angle for axle 1 (input to nonlinear steering kinematics table) from external model
IMP_STEER_RACK_CON_1	Steering rack position for axle 1 (input to nonlinear steering kinematics table) from external model
IMP_DSTEER_CON_L1 IMP_DSTEER_CON_R1	Steering gear angular rate for wheels L1 and R1 from external model
IMP_DSTEER_RACK_CON_L1 IMP_DSTEER_RACK_CON_R1	Steering rack speed for wheels L1 and R1 from external model
IMP_STEER_CON_L1 IMP_STEER_CON_R1	Steering gear output angle for wheels L1 and R1 (input to nonlinear steering kinematics table) from external model
IMP_STEER_RACK_CON_L1 IMP_STEER_RACK_CON_R1	Steering rack position for wheels L1 and R1 (input to nonlinear steering kinematics table) from external model

The table descriptions give the behavior of these variables when an option to replace parts of the system has been chosen so that the steering rack (or gear) is defined entirely in external code such as Simulink or VS Commands. However, they can be used in combination with the internal system to augment its behavior. You will note that there are separate variables for the left and right sides in addition to the single variables for the entire gear. This does not imply that there are two racks or gears, but that the value of the output of the gear that is sent as input to the kinematic tables for the wheel steer motion can be modified separately for each side.

This capability was provided to support advanced users wishing to model exotic steering systems such as those controlled by individual actuators for each side. Such systems exist on certain specialized equipment like planetary rover robots, and on the rear suspensions of some cars and off-highway vehicles.

Since there is no direct internal counterpart to these variables, no output variables for them automatically exists. Users should create output variables using `DEFINE_OUTPUT` to enable plotting of their values. Likewise, the values imported do not modify the calculated rack position and speed. Since there are two imported values (left and right) for one rack or gear, there is no way to combine them for a single output.

> **Note** When using the separate imports for each side for rack or gear control, the causal link to the column is broken, because the position of an input gear or pinion can't be inferred from different outputs sent to each side. When using the inputs to control steering in, for example, an ADAS system that controls steering by moving the gear, you should use the imports that control both sides.

Instead of thinking of these imports as the position or speed of the rack or gear, it is helpful to think of them as inputs to the kinematic tables for the wheel steer. External models or VS Commands may refer to the position and speed of the internal rack or gear in calculations of the values of the imports.

Of course, if one of the options to replace the rack or gear is chosen as described in the following sections, the internal counterpart doesn't exist and has no internally calculated outputs.

Options 0 and 1: Internal steer, no steer

Setting `OPT_STEER_EXT` = 1 indicates that the axle is never steered and has no steering system defined for it. Steer effects resulting from suspension kinematics and compliance are still present, however. When 1 is specified, the solver code for steering kinematics is bypassed, yielding a minor efficiency improvement. Most parameters and tables relating to steering are not displayed in the echo file. None of the import variables have any effect, since the code for calculating effects of a steering system is bypassed. The default value for all axles except the first axle is 1.

A value of 0 indicates that the full steering for the axle is from the TruckSim built-in steering model. Linking to steer effects in the appropriate locations in the VS Browser sets `OPT_STEER_EXT` to 0 for that axle.

With the full internal steering model (option 0), the import variables exist and may be combined with variables from the internal model, and they support all the application options (`ADD`, `REPLACE`, `MULTIPLY`). The import variables for power steering boost are the most useful with the internal model. Other imports involve direct control over motions (rack position, road wheel steer, etc.). When using these to potentially augment the motions of an internal model, the imports for their derivatives must also be supplied.

Option 2: Replacement of steering gear.

Setting `OPT_STEER_EXT` = 2 retains the steering column and tie rod / steering arm kinematics, replacing the rack and pinion or steering gear, its dynamics, boost, and control with external elements.

When the steering gear is replaced, TruckSim has no information about properties of the gear, its dynamics, a boost system, friction, damping, etc. Things that are calculated in the external model must have user-created import variables to plot them with the Visualizer, or to use in any other way. Table 5 lists the import variables that must be provided by the external model, and Table 6 lists the output variables that are probably needed by the external model.

Table 5. Variables to import when replacing the steering rack / gear.

Variable	**Description**
`IMP_DSTEER_CON_`(*axle*)	Output speed of the gear for (*axle*)
`IMP_STEER_CON_`(*axle*)	Output angle of the gear for (*axle*)
`IMP_DSTEER_RACK_CON_`(*axle*)	Output speed of the rack for (*axle*)
`IMP_STEER_RACK_CON_`(*axle*)	Output position of the rack for (*axle*)
`IMP_DSTEER_CON_`(*whl*)	Output speed of the gear for (*whl*) (`L1`, `R1`, etc.)
`IMP_STEER_CON_`(*whl*)	Output angle of the gear for (*whl*) (`L1`, `R1`, etc.)
`IMP_DSTEER_RACK_CON_`(*whl*)	Output speed of the rack for (*whl*) (`L1`, `R1`, etc.)
`IMP_STEER_RACK_CON_`(*whl*)	Output position of the rack for (*whl*) (`L1`, `R1`, etc.)
`IMP_R_STR_EXT_`(*whl*)	Instant overall steer ratio for (*whl*) (`L1`, `R1`, etc.)
`IMP_M_TBAR_EXT`	Reaction torque from gear to column

Table 6. Output variables for replacing the steering rack / gear.

Variable	**Description**
`STEER_SW`	Steering wheel (column) angle
`STRAV_SW`	Steering wheel (column) angular rate
`F_Trd(`*whl*`)`	Tie rod force at rack in the local rack direction *or*
`M_Trd(`*whl*`)`	Moment due to tie rod force at the steering gear output

Option 3: Replacement of entire system except tie rod / steer arm kinematics

Setting `OPT_STEER_EXT` = 3 replaces everything except the tie-rod and steer arm kinematics. When the steering gear and column are replaced, TruckSim has no information about properties of the column or gear, their dynamics, kinematic links, a boost system, friction, damping, etc. Things that are calculated in the external model must have user-created import variables to plot them with VS Visualizer, or to use in any other way. Table 7 lists the import variables that must be provided by the external model, and

Table 8 lists the output variables that are typically needed by the external model.

Table 7. Variables to import when replacing the column and steering rack / gear.

Variable	**Description**
IMP_DSTEER_CON_(*axle*)	Output speed of the gear for (*axle*)
IMP_STEER_CON_(*axle*)	Output angle of the gear for (*axle*)
IMP_DSTEER_RACK_CON_(*axle*)	Output speed of the rack for (*axle*)
IMP_STEER_RACK_CON_(*axle*)	Output position of the rack for (*axle*)
IMP_DSTEER_CON_(*whl*)	Output speed of the gear for (*whl*) (L1, R1, etc.)
IMP_STEER_CON_(*whl*)	Output angle of the gear for (*whl*) (L1, R1, etc.)
IMP_DSTEER_RACK_CON_(*whl*)	Output speed of the rack for (*whl*) (L1, R1, etc.)
IMP_STEER_RACK_CON_(*whl*)	Output position of the rack for (*whl*) (L1, R1, etc.)
IMP_R_STR_EXT_(*whl*)	Instant overall steer ratio for (*whl*) (L1, R1, etc.)
IMP_STEER_T_IN	Steering input torque

Table 8. Output variables for replacing the column and steering rack / gear

Variable	**Description**
STEER_SW	Steering wheel angle (control input)
STRAV_SW	Steering wheel angular rate (control input)
M_SW	Steer torque input (open loop control)
F_Trd(*whl*)	Tie rod force at rack in the local rack direction *or*
M_Trd(*whl*)	Moment due to tie rod force at the steering gear output

Option 4: Replacement of entire steering system

When the steering system is entirely replaced (OPT_STEER_EXT = 4), TruckSim has no information about properties of any components, their dynamics, kinematic links, a boost system, friction, damping, etc. Things that are calculated in the external model must have user-created import variables to plot them with VS Visualizer, or to use in any other way. Table 9 lists the import variables that must be provided by the external model, and Table 10 lists the output variables that are typically needed by the external model.

Table 9. Variables to import when replacing the entire steering system

Variable	**Description**
IMP_DSTEER_(*whl*)	Steer speed of (w*hl*) (L1, R1, etc.)
IMP_STEER_(*whl*)	Steer angle of (*whl*) (L1, R1, etc.)
IMP_R_STR_EXT_(*whl*)	Instant overall steer ratio for (*whl*) (L1, R1, etc.)
IMP_STEER_T_IN	Steering input torque

Table 10. Output variables for replacing the entire steering system

Variable	Description
`STEER_SW`	Steering wheel angle
`STRAV_SW`	Steering wheel angular rate
`M_SW`	Steer torque input (open loop control)
`F_Trd(`*`whl`*`)`	Tie rod force at rack in the local rack direction *or*
`M_Trd(`*`whl`*`)`	Moment due to tie rod force at the steering gear output

The Steering System Screen

Two screens are available to assemble the properties of the steering system. Figure 10 shows the **Steering System** screen that defines steering properties for one axle.

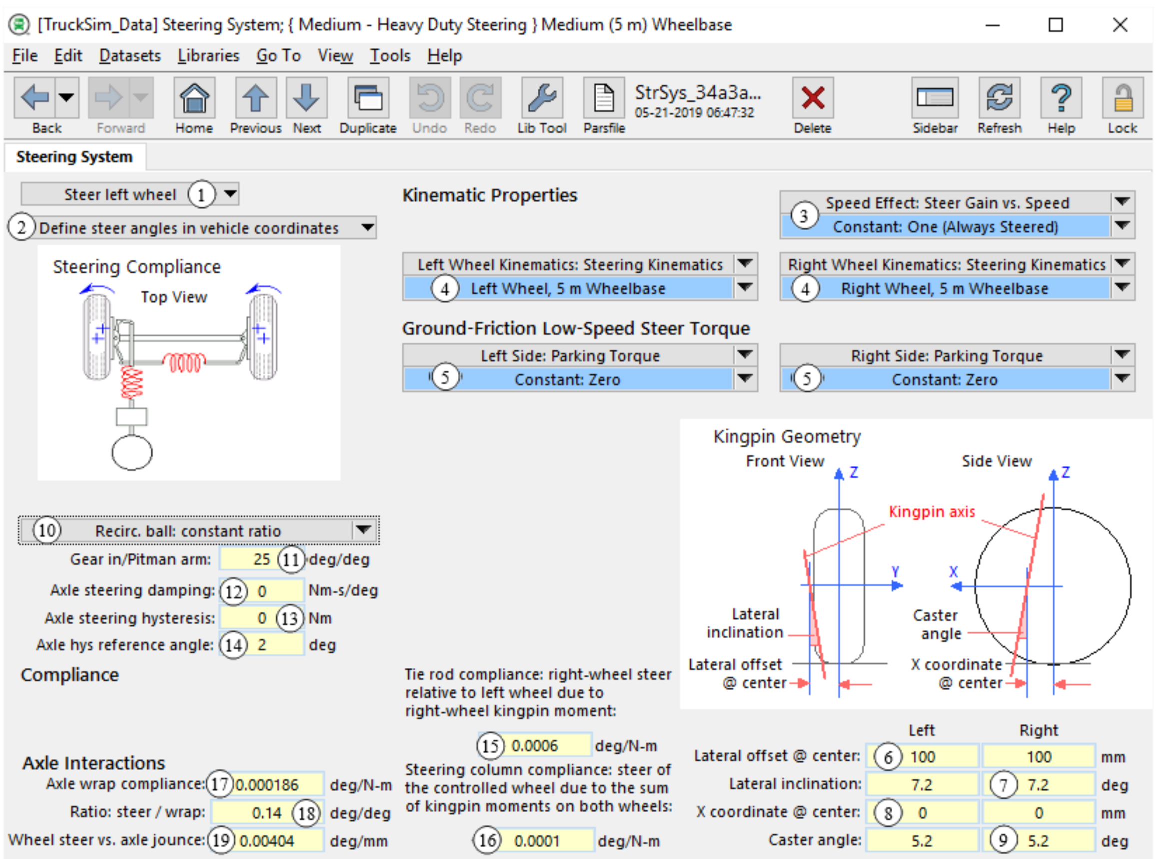


*Figure 10. The **Steering System** screen with asymmetric steer.*

User Settings and Controls

(1) Pull-down control for choosing the linkage type. In asymmetric systems (typical of heavy trucks), one wheel is controlled by a direct linkage and is therefore subject to less compliance effects (keyword = `OPT_CS`). In North America and areas where travel is on the right-hand side of the road, the left wheel is typically controlled (`OPT_CS` = 1). In Japan, England, and

countries where travel is on the left-hand side of the road, the right wheel is typically controlled (`OPT_CS` = 2). Light and medium duty trucks more typically have symmetric steer (`OPT_CS` = 0). “Symmetric steer” in this context doesn’t mean that the steer of the two sides is identical. It means only that the steering gear controls each wheel through a linkage to each wheel.

2 Drop-down list for specifying the definition of the road wheel steer angle (Figure 11).

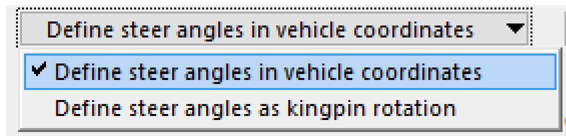


Figure 11. Steering angle drop down menu.

The first selection, **Define steer angles in vehicle coordinates**, is the default selection. It specifies that the road wheel steer angles are defined with respect to the vehicle coordinates. Steer is the angle formed by the line of intersection of the wheel plane with the vehicle X-Y plane, and is the angle typically measured on kinematic test rigs. The second selection, **Define steer angles as kingpin rotation** specifies that the road wheel steer angle s are defined with respect to the steering axis (kingpin). This selection might be more convenient if steer angles are measured using transducers mounted on the suspension, or if they are calculated from steering geometry factors such as steering arm length and rack translation.

3 Link to a **Steering System: Rear Wheel Gain** data set. This defines a speed-dependent multiplier that can be applied the steering control input to any axle except the first. To disable steering for a rear axle, set this link to a data set with a gain of zero for all speeds.

4 Links to **Steering System: Kinematics for One Wheel** data sets. Each linked data set describes a shaping function that is combined with the steering gear ratio 1 to determine the steer of a road wheel as a function of steering wheel angle, at the nominal suspension position and in the absence of tire forces, without accounting for speed effects.

5 Optional links to **Steering: Parking Torque** data sets. Each linked data set describes an additional resistive torque to be added to the kingpin moment as a function of wheel vertical load and vehicle speed.

6 Lateral offset @ center (keyword = `L_KPO`). Lateral distance that the center plane of the wheel lies outside the kingpin axis. This distance is taken along the spin axis of the wheel.

7 Lateral inclination (keyword = `A_KPI`). Kingpin axis inclination relative to the X-Z plane of the axle (or vehicle if the suspension is independent). The inclination is positive if the axis goes away from the vehicle as it goes down, as shown in the figure on the screen.

8 X coordinate @ center (keyword = `X_KPO`). Longitudinal position of the wheel spin axis relative to the kingpin axis. This coordinate is positive if the wheel is in front of the axis. (The figure on the screen shows a geometry with a negative X coordinate.)

9 Caster angle (keyword = `A_CASTER`). Kingpin axis inclination when viewed from the side of the vehicle. The caster is positive when the axis goes forwards as it goes down, as shown in the figure on the screen.

(10) Link to set the steering gear kinematics. A simple ratio may be selected for each type, or a table may be linked to describe variable ratio systems.

(11) Steering gear ratio for this axle (keyword = `R_GEAR_STR`). This is the ratio between the steering wheel angle and the nominal steer angle of the road wheels. Overall, the steer of the road wheels is the product of the steering wheel angle, the inverse of this gear ratio, and two nonlinear shaping functions (3), (4).

> **Note** The steering wheel angle is divided by this number, so never set it to zero. (To disable steering for an axle, use the **Steering System: Rear Wheel Gain** link (3))

(12) **Steering Gear Damping** (keyword = `D_GEAR`) or **Steering Rack Damping** (keyword = `D_RACK`). This is the damping coefficient for the steering gear. For recirculating ball steering, this value is based on the pitman arm angular speed. For a rack and pinion system, it is based on the rack translation speed. When the **Steering Column and Assist** linked on the **Vehicle** screen doesn't specify power steering, or if this data set is linked on any axle other than axle 1, this field has no effect on vehicle dynamics,

(13) **Steering Gear Hysteresis** (keyword = `HYS_GEAR`) or **Steering Rack Hysteresis** (keyword = `HYS_RACK`). The hysteresis (friction) at the steering gear. This is one-half the difference in torque (or force, in the case of rack and pinion systems) measured when steering to the left and to the right. It represents the total friction in the gear, tie rods, ball joints, kingpins, etc.

(14) **Steering gear reference hysteresis angle** (keyword = `BETA_GEAR`) or **Steering rack reference hysteresis length** (keyword = `BETA_RACK`). When the direction of steering is reversed, the friction (hysteresis) does not jump instantly from one limit to the other – it takes a certain amount of displacement to make the transition. A parameter called *Beta* defines the rate at which the friction makes this transition. Beta is sometimes called a spatial time constant, appearing in equations the same as time constant would in first-order differential equations. However, it is expressed in units of displacement (degrees or mm) rather than time.

Beta is about 1/3 of the displacement needed to travel through 95% of the change in force (or torque) when changing direction of motion. For example, if it takes 1.5mm to cover 95% of the hysteresis, then beta would be 0.5mm.

> **Note** Parameters (12), (13), and (14) have no effect on vehicle dynamics when the steering system is manual (no power assist) and the steering wheel angle is controlled by either open- or closed loop control. The settings for Axle 1 (the controlled axle) do, however, figure in the steering torque calculation when steer torque is not obtained from a lookup table. When the system is power assisted or in torque control, settings for axle 1 do affect vehicle dynamics. Settings for axles other than axle 1 do not, because those axles are assumed to be servo-controlled.

(15) Tie rod compliance for steer of second wheel (keyword = `CS_MZ_ROD`). This is the compliance ratio between steer of the wheel controlled by a tie rod and the steering moment applied to that wheel alone.

(16) Steering column/system compliance (keyword = `CS_MZ_SHAFT`). This is the compliance ratio between the steer of the controlled wheel and the total steering moment applied to both wheels of the axle.

(17) Axle wrap compliance (keyword = `C_WRAP`). This parameter only applies for solid-axle suspensions. It is a compliance ratio between the forward pitch of an axle relative to the sprung mass, and the total wheel spin torque (braking/acceleration).

(18) Ratio between steer and axle wrap (keyword = `R_WRAP_STR`). This is the steer applied to the axle due to axle wrap It results from the geometry and angularity of the drag link.

(19) Ratio between wheel steer and solid-axle jounce (keyword = `R_BMP_STR`). bump-steer effect is due to interactions between vertical movements of the axle and the asymmetric steering connection that induces a steering angle on the controlled wheel.

When the pull-down for setting the linkage-type (1) is set to **Steer Symmetrical** the appearance of the screen is as shown in Figure 12. Alternate controls are displayed to configure the symmetrical system.

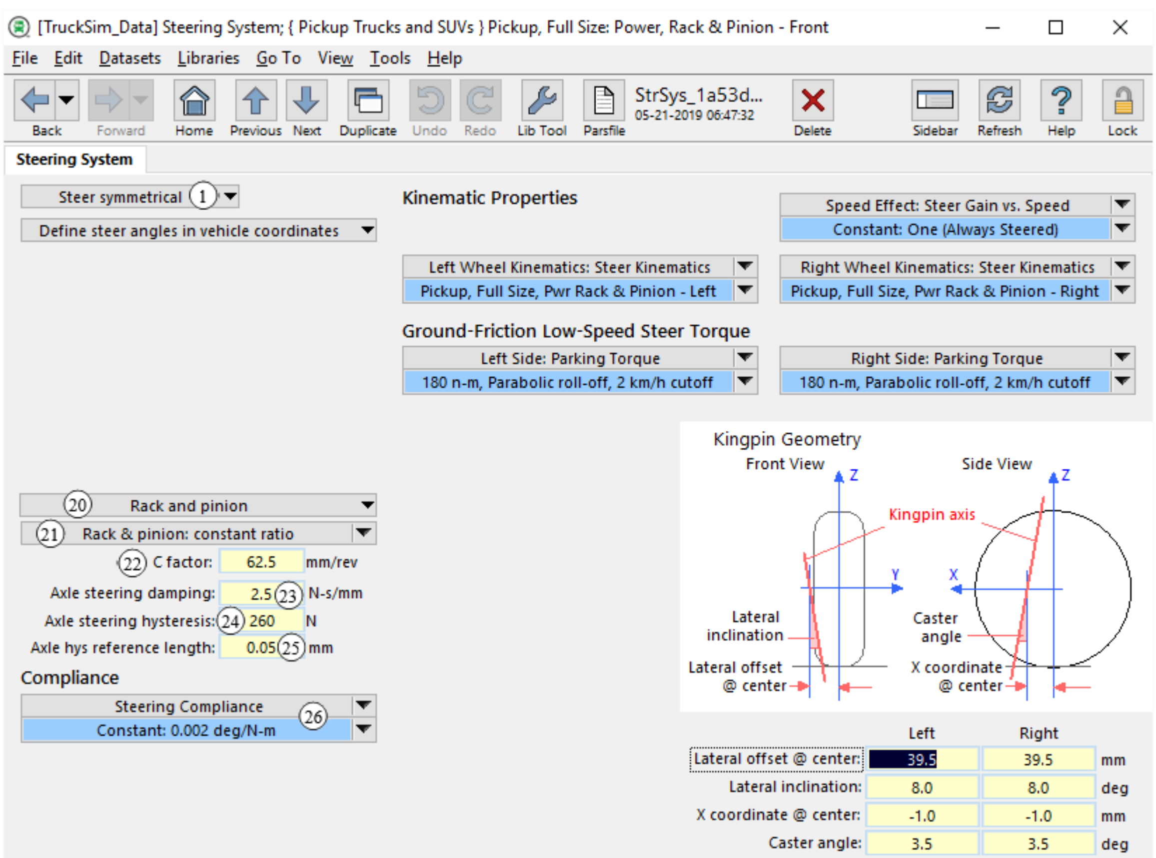


Figure 12. Steering System: Steering system screen with symmetric steer.

Note "Symmetrical" does not imply that the linkage on the two sides are mirror images. It indicates only that the output of the steering gear (rack or Pitman arm) is connected to both wheels, instead of just one.

20 Pull down to choose the steering gear type for a symmetrical steering system. The choices are "Rack and Pinion" and "Recirculating Ball". "Recirculating Ball" is used for any steering gear type where both the input and output are rotations (Worm and sector, worm and roller, etc.) (keyword = `OPT_RACK`)

21 Link to set the steering gear kinematics. A simple ratio may be selected for each type, or a table may be linked to describe variable ratio systems.

22 For rack and pinion systems the ratio is specified by a "C-factor", the distance the rack travels in mm for one rotation of the pinion. (keyword = `RACK_TRAVEL_COEFFFICENT`) For recirculating ball systems, the ratio is degrees of input gear rotation per degree of Pitman arm rotation. (keyword = `GEAR_ROT_COEFFFICENT`)

23 **Steering Gear Damping** (keyword = `D_GEAR`) or **Steering Rack Damping** (keyword = `D_RACK`). This is the damping coefficient for the steering gear. For recirculating ball steering, this value is based on the pitman arm angular speed. For a rack and pinion system, it is based on the rack translation speed.

24 **Steering Gear Hysteresis** (keyword = `HYS_GEAR`) or **Steering Rack Hysteresis** (keyword = `HYS_RACK`). The hysteresis (friction) at the steering gear. This is one-half the difference in torque (or force, in the case of rack and pinion systems) measured when steering to the left and to the right. It represents the total friction in the gear, tie rods, ball joints, kingpins, etc.

25 **Steering gear reference hysteresis angle** (keyword = `BETA_GEAR`) or **Steering rack reference hysteresis length** (keyword = `BETA_RACK`). When the direction of steering is reversed, the friction (hysteresis) does not jump instantly from one limit to the other – it takes a certain amount of displacement to make the transition. A parameter called Beta defines the rate at which the friction makes this transition. Beta is sometimes called a spatial time constant, appearing in equations the same as time constant would in first-order differential equations. However, it is expressed in units of displacement (degrees or mm) rather than time.

Beta is about 1/3 of the displacement needed to travel through 95% of the change in force (or torque) when changing direction of motion. For example, if it takes 1.5mm to cover 95% of the hysteresis, then beta would be 0.5mm.

Note Parameters 22, 23, and 24 have no effect on vehicle dynamics when the steering system is manual (no power assist) and the steering wheel angle is controlled by either open- or closed loop control. The settings for Axle 1 (the controlled axle) do, however, figure in the steering torque calculation when steer torque is not obtained from a lookup table. When the system is power assisted or in torque control, settings for axle 1 do affect vehicle dynamics. Settings for axles other than axle 1 do not, because those axles are assumed to be servo-controlled.

(26) Link to **Steering System: Compliance** dataset. This linked dataset defines the overall steering system compliance effects for the wheels on this axle. Each is a nonlinear shaping table that is multiplied by the total moment of the left and right wheels about their kingpin axes to obtain the compliance steer effect.

The Steering Column and Assist Screen

This screen (Figure 13) is available to assemble the properties a steering system that appear only once on the vehicle (not specified for each individual axle).

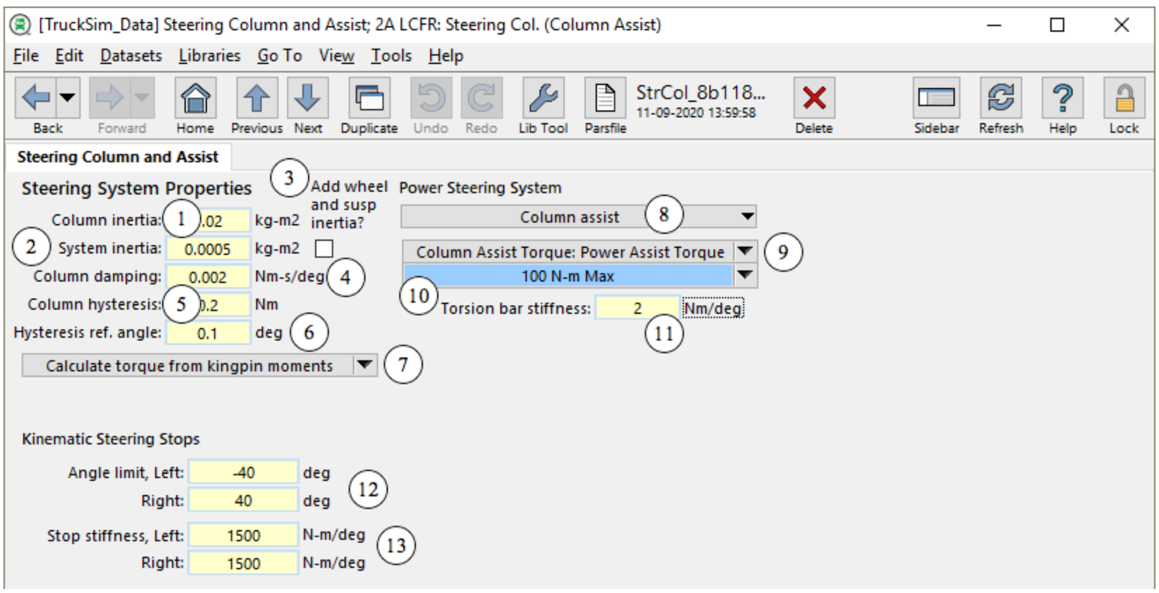


Figure 13. Steering Column and Assist: Steering parameters for system control

This screen is linked from a **Vehicle: Lead Unit** screen to supply information about the steering column and (optional) power steering assist.

User Settings and Controls

(1) **Steering Column Inertia** (keyword = `I_COL`). The moment of inertia of the steering wheel and rotating column components. When the steering input is by steer angle (either by open-loop control or closed-loop “driver model” control), this parameter has no effect. Since the acceleration of the column is unknown when the angle is controlled, TruckSim can’t calculate an inertial torque effect. When input is by open-loop torque control, this parameter is used.

(2) **Steering System Inertia** (keyword = `I_GEAR_IN`). The moment of inertia of the steering gear and linkage components. System inertia is indexed to the input gear. It represents the torque required to produce an angular acceleration at the input gear. This quantity may or may not include the moment of inertia of the steered wheel-end components (steering knuckle,

brake, wheel, and tire) about the steering axis based on the setting of OPT_I_GEAR_IN (see page 22 and next item in this list). In most cases, the value entered here will not include a contribution from the wheel-end components. In this case, the system inertia is a consequence of lumping the mass of a rack and tie rods (or the inertia of an output gear, Pitman arm, and mass of tie rods) with that of the input gear. For example, if a rack and pinion has a C-factor of 40 mm/rev, the pinion pitch radius is 0.00637 m. Four kg of rack and tie rod mass would contribute mr^2 or 0.000162 kg-m^2 to the system inertia. This is an important fact to keep in mind: If an adjustment is made to the C-factor, the system inertia should be adjusted.

3 **Wheel/Suspension Contribution to Steering Inertia** (keyword = OPT_I_GEAR_IN). When this box is checked, the OPT_I_GEAR_IN parameter is turned on (= 1), meaning the VS Math Model automatically calculates an equivalent inertia based on the properties of the suspension and wheel/tire, and adds that to the I_GEAR_IN value entered in the adjacent yellow field. If this box is unchecked, the I_GEAR_IN value entered in the adjacent yellow field should include the effects of the unsprung masses rotating about the steering axes.

4 **Steering Column Damping** (keyword = D_COL). A viscous damping coefficient applied to the steering column.

5 **Steering Column Hysteresis** (keyword = HYS_COL). Steering column hysteresis torque. This is one-half the difference in torque measured when turning the steering wheel to the left and to the right, for the column components only. It represents friction in the column components.

6 **Steering Column Reference Hysteresis Angle** (keyword = BETA_COL). When the direction of steering is reversed, the friction (hysteresis) torque does not jump instantly from one limit to the other – it takes a certain amount of displacement to make the transition. A parameter called beta defines the rate at which the friction torque makes this transition. Beta is sometimes called a spatial time constant, appearing in equations the same as time constant would in first-order differential equations. However, it is expressed in units of displacement (degrees) rather than time.

Beta is about 1/3 of the angle needed to travel through 95% of the change in torque from one limit to the other. For example, if it takes 1.5° to cover 95% of the torque hysteresis, then beta would be 0.5°.

7 Drop-down list for selecting the method used to calculate the torque at the steering wheel (Figure *14*).

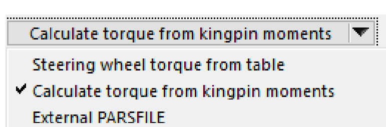


Figure 14. Options for calculating torque at the steering wheel.

If Steering wheel torque from table is selected, you can link to a table that defines the steering wheel torque as a function of total kingpin torque and vehicle speed.

If **Calculate from kingpin moments is selected,** the method used to obtain steering wheel torque depends on the control input to the steering. When steering is controlled by torque input, the specified input torque is simply passed to the output variable for plotting. When steering is controlled by steering wheel angle input (either open loop or by the driver model), the kingpin torques, instantaneous steer ratio, power steering assist, column damping, and column hysteresis are all used to calculate a steering wheel torque. The torque required to accelerate the inertia of the steering column is not included in the calculation, because the open loop control specifies a steer angle, and the driver model produces a steer angle, so the second derivative of the steer angle (the angular acceleration) is undefined in the VS solvers.

8 Drop-down list for selecting the power assist type, if any, for the front wheels.

9 Optional link to a dataset describing assist torque or force of a power assisted steering system. They are displayed only when one of the power assist options is selected. The number and type of links depends on the choice of steering systems made with drop-down lists 7. One link to a **Steering: Power Assist Torque** or **Steering: Power Assist Force** dataset is displayed. The type displayed depends on the gear type selected.

10 The power assist screens include a field to define a time constant for the power steering system. Since the output of the system cannot change instantaneously in response to a change in input, a simple time constant is used to define a first-order delay in system

11 **Torsion Bar Stiffness** (keyword = `TBAR`) If one of the power assisted steering options is selected, this field is displayed to specify the stiffness of the power steering gear torsion bar.

12 **Steering Stop Angle Limits** (keywords = `A_STR_STOP_L`, `A_STR_STOP_R`) Road wheel steer angles at which steering stops are encountered. Normally, the left wheel has a negative value (outboard wheel when turning right), and the right wheel a positive value (outboard wheel when turning left).

13 **Steering Stop Stiffness** (keyword = `K_STR_STOP_L`, `K_STR_STOP_R`) Stiffness of the steering stop device at each wheel. Normally, these should be set to zero (disabled) if steering is controlled by steer angle, because the steering control will continue to steer causing very high steer forces and the model may become unstable. When steering control is by torque, however, the steer stops prevent unrealistic steer angles in the system.

Using the Driver Model with External Steering Models

Each option for replacing elements of the steering system with external models can accept either open- or closed-loop control input. The steering command signal may be modified using the import variable `IMP_STEER_SW`, with one of the option settings **Add**, **Replace**, or **Multiply** selected in the drop-down list on the **I/O Channels: Import** screen.

When the math model is set for open-loop control, an imported steering command may modify one from a table. In closed-loop control (driver model) the import modifies the behavior of the driver model.

An optional keyword `OPT_DRIVER_ACTION` (for advanced users, set by typing the keyword and its value into a miscellaneous yellow field), controls the behavior of the driver model, if it is selected.

Setting OPT_DRIVER_ACTION to 0 causes the driver model to perform its calculations as usual, but the resulting control is not applied to the steering wheel. This mode can be used to provide a control input for an externally defined steering system, such as steer by wire. It can be considered a steer "request" from the driver. The calculated driver control is available as an export (in the variable STEER_DM) for use in external software such as Simulink, or in equations defined with VS commands. Setting OPT_DRIVER_ACTION to 1 (the default) causes the driver model to apply the calculated steering wheel angle to steer the vehicle. If you use OPT_DRIVER_ACTION set to 0, keep in mind that you must provide a steering wheel angle or it will always be zero.