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Sign Conventions in the Steering System

This technical memo discusses sign conventions in the TruckSim Steering Systems. Interpretation of output variables involving steering has occasionally caused confusion, and this is intended to clarify the subject. Special attention is given to the differences between rack and pinion systems with the rack ahead of the axle vs. systems with the rack behind the axle.

Main Elements of the Systems

Each steering system model in TruckSim consists essentially of three elements: the steering column, the steering rack or gear, and the linkage connecting the gear to the steered wheel ends. Each of these may have forces or moments applied or passed from one to the next and may be connected by constraints (defined by coefficients or tables of data) describing linkages and so on.

These elements might represent degrees of freedom in the model or not, depending on whether the steering is controlled by steer angle or steer torque, and whether the system has power assist.

Refer to the TruckSim Steering Systems manual for more detailed discussion of system degrees of freedom.

Sign Conventions on Motions of the System Elements

In a purely mathematical sense, the signs (+/-) assigned to each force, moment or kinematical effect matter only to the extent that a given input produces the desired output. However, it can be helpful to think of the physical arrangement of parts, so typical arrangements are described here.

> **Note** The arrangements of components discussed here are typical steering systems. Advanced users might use other sign conventions to describe unusual systems.

In these discussions, the sign conventions for items influencing the motion (system description and inputs) or items calculated by the models (outputs) follow the same sign convention used throughout TruckSim: motion and forces to the left are positive, counterclockwise angles and moments are positive.

Steering Wheel and Column

A positive steering wheel angle, angular rate, or angular acceleration indicates counterclockwise rotation of the wheel, and steer to the left. Intermediate shaft rotation is positive output (counterclockwise, leftward) for positive input.

Note that acceleration of the steering wheel and column is only known when the steering system is controlled by torque input. A positive input torque is in the direction of positive rotation (counterclockwise, leftward). The output variable for steer torque is just the input torque and has the same sign. When the system is controlled by setting the steering wheel angle, the output variable for the steer torque is the reaction torque from the wheel to the driver (steering left produces a negative reaction torque to the driver).

The contributions of steering column damping and hysteresis (friction) always oppose the angular speed (damping) and direction of motion (hysteresis).

When power steering is used, a torsion bar (spring) exists between the column and the input gear of the steering rack or gear. A positive rotation of the wheel rotates the input to the torsion bar in a positive direction. The torsion bar angle is the column angle minus the angle of the input gear, and a positive angle produces a positive torque to be applied to the gear.

With power steering in torque control, the input torque (positive counterclockwise), damping and hysteresis torques (opposing motion) and the reaction from the torsion bar (positive torsion bar torque produces negative reaction) are applied to the column inertia in an ordinary differential equation to calculate its motion.

Steering Gear with Asymmetric Systems

In TruckSim, the most commonly chosen steering configuration is called “Asymmetric Steer”. In this system, a steering gear is normally mounted ahead and above the axle. The column input rotation produces an output rotation of a Pitman arm in a vertical plane about an axis parallel to the sprung mass Y coordinate direction, and generally pointing down. For a system controlling the left wheel, a positive input rotation produces a negative (clockwise) output, moving the end of the Pitman arm forward. For a system controlling the right wheel, a positive input rotation produces a positive (counterclockwise) output, moving the end of the Pitman arm rearward. A Drag link connects to a steering arm on the controlled wheel to steer it. In most cases, users ignore the positive/negative sense of the Pitman arm rotation, because it requires coordination with the tables describing the rest of the linkage kinematics.

Recirculating Ball Steering Gear

In TruckSim, there are two symmetric alternative steering gear types to the asymmetric system. The first of these is called “Recirculating Ball” although it includes other types such as “Worm and Roller” or “Worm and Sector”. All these types and perhaps others are distinguished by the fact that they receive rotation as an input and produce rotation as an output. The output rotation is typically the rotation of a Pitman arm. The Pitman arm connects to one of various types of linkages to steer the wheels, mot commonly a “parallelogram” linkage with a relay rod, idler arm and two tie rods.

In these systems, positive inputs produce positive outputs. A positive gear ratio or positive table slope produces positive output for positive input. And a negative ratio or slope produces negative output for positive input.

When power steering is not used, the output motion is calculated from the input using the specified ratio or table applied to the column motion.

With power assist, the torsion bar torque, damping and hysteresis torques and moments due to tie rod forces, and boost torque are applied to the system inertia in an ordinary differential equation to calculate its motion. The system inertia includes the gear inertia plus the masses of the linkage and tie rods transformed to an inertia at the input gear.

In contrast to rack and pinion systems, the sign on the gear ratio or slope of the table doesn't directly imply whether the system is mounted ahead or behind the axle. The sign on the ratio just indicates whether the rotation of the pitman arm is counterclockwise (positive) or clockwise (negative).

The Pitman arm itself might be mounted to point forward or aft of the gear rotation axis. A positive rotation of a Pitman arm pointing to the rear would indicate negative (rightward) motion of the linkage.

The most common arrangement places the gear forward of the axle, with a negative gear ratio and trailing Pitman arm. In this case the column rotation produces negative (clockwise) rotation of the pitman arm. A parallelogram linkage arrangement produces positive (leftward) steer at the wheel, so positive steering wheel angles cause positive steer.

Steering Rack

When rack and pinion steering is specified without power steering, a positive rotation of the steering column produces a positive rotation of the pinion gear. With power steering, a positive rotation of the column rotates the input of the torsion bar in the positive direction. The output of the torsion bar is the pinion angle. The torsion bar angle is the column angle minus the pinion angle. The torsion bar torque has the same sign as the torsion bar angle.

If the C-factor is given positive sign or, in the case of configurable functions to define a non-linear ratio, a table with positive slope, the rack motion is positive (leftward) for a positive pinion angle. Positive rack motion for positive column rotation is typical of systems with the rack ahead of the axle.

If the C-factor or the slope of a table describing the rack ratio is negative, the rack motion is negative (rightward) for a positive pinion angle. Negative rack motion for positive column rotation is typical of systems with the rack behind the axle.

When power assist is not used, the rack motion results entirely algebraically from multiplications and table-lookups. The damping and hysteresis forces are calculated using the algebraically determined rack position and speed.

With power assist, the torsion bar torque, damping and hysteresis forces and tie rod forces, and boost force are applied to the system inertia in an ordinary differential equation to calculate its motion. The system inertia includes the pinion inertia plus the masses of the rack and tie rods transformed to an inertia at the pinion. The rack forces are transformed to pinion torques. Calculation of tie rod forces is discussed in the section on wheel end kinematics, later in this document.

Wheel End Kinematics, Moments and Forces

The steering linkage and steer arm combine to produce the final element in the steering system kinematic chain. Typically, linkages ahead of the axle move in the positive direction to produce positive steer by moving the end of the forward-pointing steer arm leftward. Linkages behind the axle move in the negative direction to produce positive steer by moving the end of the rearward-pointing steer arm to the right.

Configurable functions with non-linear tables are nearly always used to describe the motion resulting from the articulation of the linkage and steer arm.

In a slowly increasing steer maneuver to the left, the self-aligning torque and mechanical trail combine to produce a negative kingpin torque attempting to self-center the steering. In a rack and pinion system with the rack behind the axle, the negative kingpin torque and the steering arm pointing backward produce a positive force in the tie rod, attempting to move the rack to the left, or back toward center.

In a rack and pinion system with the rack ahead of the axle, the negative kingpin torque and the steering arm pointing forward produce a negative force in the tie rod, attempting to move the rack to the right, or back toward center.

In the common arrangement of recirculating ball systems, negative kingpin torque and the steering arm pointing forward produce a negative force in the linkage. The negative force applied to the Pitman arm pointing aft produce a positive (counterclockwise) torque at the pitman arm. Combined with a negative gear ratio, the positive Pitman arm torque attempts to move the gear back toward center.

Power Steering Boost

The steering assist table must have appropriate slope so that an input at the torsion bar produces boost in the appropriate direction.

The Most Common Steering Linkage Arrangements

Torsion bar stiffness and hysteresis and damping parameters are positive in each case described below.

Asymmetric Systems

In the common implementations of asymmetric steer controlling the left wheel, the gear ratio is negative, and the tables for wheel kinematics have positive values for negative inputs. When the right wheel is controlled, the ratio is positive, and the tables for wheel kinematics have positive values for positive inputs. In most cases, however, users ignore the details of sign and use a positive ratio and positive kinematic outputs. Choosing to do this has no effect on vehicle dynamics, and my be less confusing.

Rack and Pinion, Rack Ahead of Axle

In this arrangement, the C-factor or ratio table slope are positive, the wheel-end kinematic tables have positive slope, and power steering boost is positive for a positive torsion bar torque.

This means, when steering to the left (positive), the torsion bar (if present) has a positive angle, the pinion rotation is positive, the rack translation and boost are positive. A wheel-end kinematics table with positive slope implies a steering arm pointed forward and the resulting steer is positive, or to the left. Negative aligning moments produce negative (rightward) forces in the tie rods.

Rack and Pinion, Rack Behind Axle

In this arrangement, the C-factor or ratio table slope are negative, the wheel-end kinematic tables have negative slope, and power steering boost is negative for a positive torsion bar torque.

This means, when steering to the left (positive), the torsion bar (if present) has a positive angle, the pinion rotation is positive, but the rack translation and boost are negative. A wheel-end kinematics table with negative slope implies a steering arm pointed rearward and the resulting steer is positive, or to the left. Negative aligning moments produce positive (leftward) forces in the tie rods.

Recirculating Ball, Ahead of Axle, Pitman Arm Pointing Rearward

In this arrangement, the steering gear ratio or ratio table slope are negative, the wheel-end kinematic tables have negative slope, and power steering boost is negative for a positive torsion bar torque.

This means, when steering to the left (positive), the Pitman arm rotation is negative (clockwise) and the end of the rearward pointing Pitman arm moves to the left. The end of the steering arm, pointing forward, moves to the left steering the wheels to the left through the forward pointing steer arm. Negative boost assists the clockwise motion of the Pitman arm.

The aligning moments in the left turn produce negative tie rod forces applied to the trailing Pitman arm, producing positive moments. Note that from the information given, it is only possible to calculate the moments due to the tie rod forces, not the forces themselves. The kinematic tables in this case don’t provide enough information to infer the Pitman arm length. They only imply the ratio of the Pitman arm to steer arm length.

The Back-story on Sign Conventions in Steering

When a fully dynamic steering system with power assist was added to TruckSim several years ago, the internal functions used to manage the look-up tables required the data in the tables to have positive slope. Principally, this was involved in calculating an overall steer ratio for the system to be used by the closed-loop steering controller (driver controller).

As you can see in the descriptions of the various systems above, the model was still valid for any of the arrangements but required careful interpretation of the results by the user. Occasionally this caused confusion, but all steering system models in TruckSim examples conformed to this limitation.

Since then, the underlying limitations have been eliminated as the capabilities of various parts of TruckSim have been extended. However, examples, most of which carried over from earlier releases, continued to adhere to the “all-positive” convention.

In future releases a selection of different configurations will be represented in the examples. We hope this improves ease of use and eliminates confusion.