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The Design Load Condition in TruckSim

This technical memo discusses the "Design Load Condition" in TruckSim, including its meaning and use, and possible errors if it is misunderstood. Failing to understand this concept will result in incorrect definition of vehicle properties, poor correlation to physical tests or other software, and incorrect interpretation of results.

The last portion of this memo is a Case Study that examines the Design Load Condition and illustrates the effects of some of the vehicle parameters that can cause the equilibrium state of a vehicle to differ from it.

This document assumes that the reader has some familiarity with TruckSim, is capable of making new runs, exploring datasets, etc. It does not offer the step-by-step instructions needed by new users. At a minimum you should have successfully completed and understood the Quick Start Guide and be familiar with the concepts in the VS Commands reference manual.

Standard Coordinate Systems

In configuring a vehicle model, one critical step is the correct definition of the locations of all significant components and properties. If, for example, the suspension position doesn't agree with that found on the physical vehicle, the dynamics of the simulated vehicle should be expected to be different from the real vehicle.

Vehicle manufacturers specify the locations of components and systems in a coordinate system. The coordinate system must be "attached" to the vehicle in some known way, or the coordinate locations of parts relative to each other would be constantly changing. If, for example, a coordinate system were based on the ground, all the coordinates such as CG height, pitch and roll angles, and wheel locations would have to be uniquely specified if the vehicle load changed or tires were substituted.

Since the location and orientation of a thing can only be defined by giving its distance from, and orientation angles to, another thing, coordinate reference frames are necessary. Vehicles are designed within such a reference frame, with information provided about properties like mass, inertia, and suspension positions at various loads. We might refer to these loads with names like "design", "2 passenger", GVW, etc. "Ground lines" (a line representing the surface of the ground relative to the vehicle) might be shown for the various load cases. This is an important concept: The ground and the reference frame are not connected, so the vehicle may have many positions and orientations with respect to the ground.

Coordinate origins and the definitions of load cases might vary from manufacturer to manufacturer, or from industry to industry. Design conventions for trailers, for example, might be very different from those for passenger cars.

To conduct simulations, it was necessary to choose a standard method for defining the positions and orientations of all key components in TruckSim. The chosen method accommodates things like the addition of payloads or connecting a trailer to a vehicle designed without one and assists in the initial estimates of the placement of the vehicle on road surfaces that might not be flat. This method is called the "Design Load Condition" in this memo.

The Design Load Condition defines the reference for the vehicle sprung mass. (What does *zero pitch* or *zero roll* really mean?) It relates tables of suspension position and orientation to specific locations in the vehicle reference frame. (What does *zero jounce* really mean?) And it relates the suspension position to a table of spring force versus spring compression. Knowledge of the reference condition makes possible the addition of payload masses and the connection of trailers.

One of the most important concepts for TruckSim users to understand is:

The design load condition is NOT (in general) the equilibrium position of the vehicle on the ground, even if the ground is flat and at zero height in the global coordinates.

In most cases a vehicle that is brought to equilibrium will exhibit some non-zero pitch and possibly roll, and the suspension jounce will be different from the Design Load Condition.

A Summary of "Design Load Condition"

Note first that Design Load Condition is used to define the locations and orientations of key body properties and components, and to enable an algebraic estimate of the initial position of the vehicle when a simulation begins.

Second, Design Load Condition is defined separately for each vehicle unit, without consideration of payloads or trailers hitched to that unit. Each unit is handled separately because trailers can be hitched or not, and payloads can be added or removed. Design Load Condition for trailers provides only information about that trailer, without consideration of a lead unit or other trailers.

At the Design Load Condition, the sprung mass of the vehicle unit (lead unit or trailer) is at zero pitch and zero roll when the X-Y coordinate reference plane of the sprung mass is parallel to the global X-Y reference plane.

At the Design Load Condition each axle carries a portion of the weight of the sprung mass determined from the sprung mass parameters for mass, coordinates of the mass center, and X locations of the axles. When a vehicle unit has more than two axles, the distribution among them is estimated.

The weight carried by each axle is divided by 2. (Lateral offset of the CG is ignored). This weight, along with the mechanical ratio specified for the suspension, gives the spring force at Design Load is used to determine the spring compression at Design Load by an inverse table-lookup. The wheel center heights specified on the TruckSim Suspension kinematics screen define the location in the sprung mass coordinate reference frame of each wheel when it carries the design load.

The value of "Jounce" at the Design Load is found by one of two means, depending on user settings on the Suspension Kinematics screens. "Specify jounce at design load" simply assigns the value of jounce (and hence the location in the kinematics tables) to be used when the suspension carries the design load. "Define jounce from spring data" means that, having determined the spring compression, the mechanical ratio and spring compression are used to find the value to be assigned to jounce (and the location in the lookup tables) to be used when the suspension carries the design load.

Placement of the Sprung Mass Origin

The sprung mass of each unit has an associated coordinate system used to define the relative positions and orientations of mass properties, the wheels, and (optionally) a trailer hitch. The diagram does not illustrate a vehicle on the ground but uses the Design Load Condition as the standard reference condition.

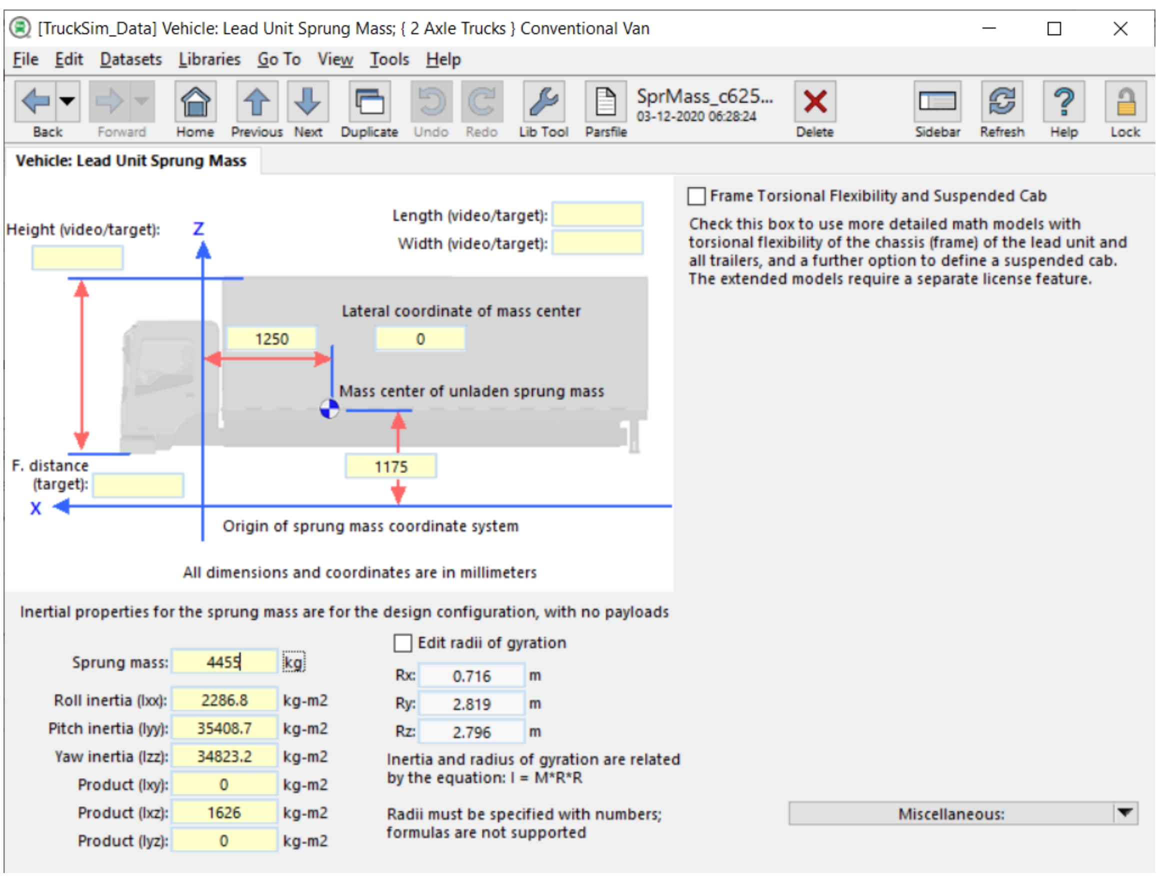

Figure 1. The **Sprung Mass** *screen references the Design Load Condition*

In Figure 1, the blue lines labeled “X” and “Z” illustrate conceptually the sprung mass coordinate system. The mass and inertia values entered here are intrinsic properties of the body. That is, they are not dependent on its position or orientation. They are, however, used to locate the origin of the sprung mass coordinate system.

The mass center height and distance behind the origin locate the body in the coordinate reference frame. In TruckSim, the X coordinate of the first axle is explicitly entered on the **Vehicle: Lead Unit** screen and is not necessarily at zero, though zero is nearly always used. Also in TruckSim, the fields for wheel center heights do not appear on the Sprung Mass screen; instead, they are specified on the **Suspension: Solid Axle System Kinematics** or **Suspension: Independent System Kinematics** screen because a spring mass can have more than two axles. For trailers, remember each unit has its own reference frame and origin, and the axle coordinates refer to that.

The inertia properties entered here are *NOT* measured about the coordinate axes. They are measured about a set of axes through the center of mass and parallel to the sprung mass reference axes. The inertias are intrinsic body properties, not dependent on position, so they must be inertias about axes through the mass center.

When the sprung mass coordinate X-Y plane is parallel to the inertial reference (global) X-Y plane, the body is defined to be at zero pitch and zero roll. When the body X axis projection onto the global X-Y plane is parallel to the global X axis, the body is at zero yaw.

Since the height of the center of mass is measured from the reference for Z = 0, and at this point nothing is known about the suspension or the road surface, the origin is *NOT* on the ground and the mass center height is *NOT* the height above the ground. In fact, the origin and the entire sprung mass reference frame are attached to, and move with, the sprung mass.

Interpretation of the Wheel Center Height

Once the body properties of the sprung mass are located in its reference frame, the location of the wheels must also be defined. The wheel center position is used TruckSim to obtain the correct values for *Jounce* and *Spring Compression* at the Design Load Condition. If this relationship isn’t correct, the values for suspension kinematic properties will be incorrect.

The Wheel Center Height is the location of the wheel center in the sprung mass coordinate reference frame when the sprung mass is at zero pitch and roll, and the suspension carries the Design Load. That is, each suspension carries one-half the axle load determined from the mass and CG distance behind the origin. Note that no information about tires is involved here.

The Wheel Center Height is *NOT*, in general, the static loaded radius of the tires. If the front and rear wheel center heights are equal, and the mass distribution to the axles is not 50/50, and the tires are identical, the tires will carry different loads when the simulation starts, and the tires will compress by different amounts. This causes the car to assume a non-zero pitch angle at equilibrium.

Wheel Center Height, Jounce, and Springs

Given the location of the wheels in the Sprung Mass Reference Frame at a known load, two other pieces of information can be related to the Design Load Configuration: *Jounce* and *Spring Compression*.

In general use, *jounce* is understood to mean vertical upward displacement of the wheel relative to the sprung mass. Downward displacement is known as *rebound* or *negative jounce*. In simulation, a very precise meaning must be defined because many suspension characteristics are related to jounce.

In TruckSim, these relationships are ordinarily defined by lookup tables of various kinematic motions (toe, camber, fore/aft and lateral movement, *"dive"* or side view rotation) versus jounce.

Figure 2 shows the TruckSim **Susp: Independent Kinematics** for an independent suspension. There is a similar screen for solid axle suspensions.

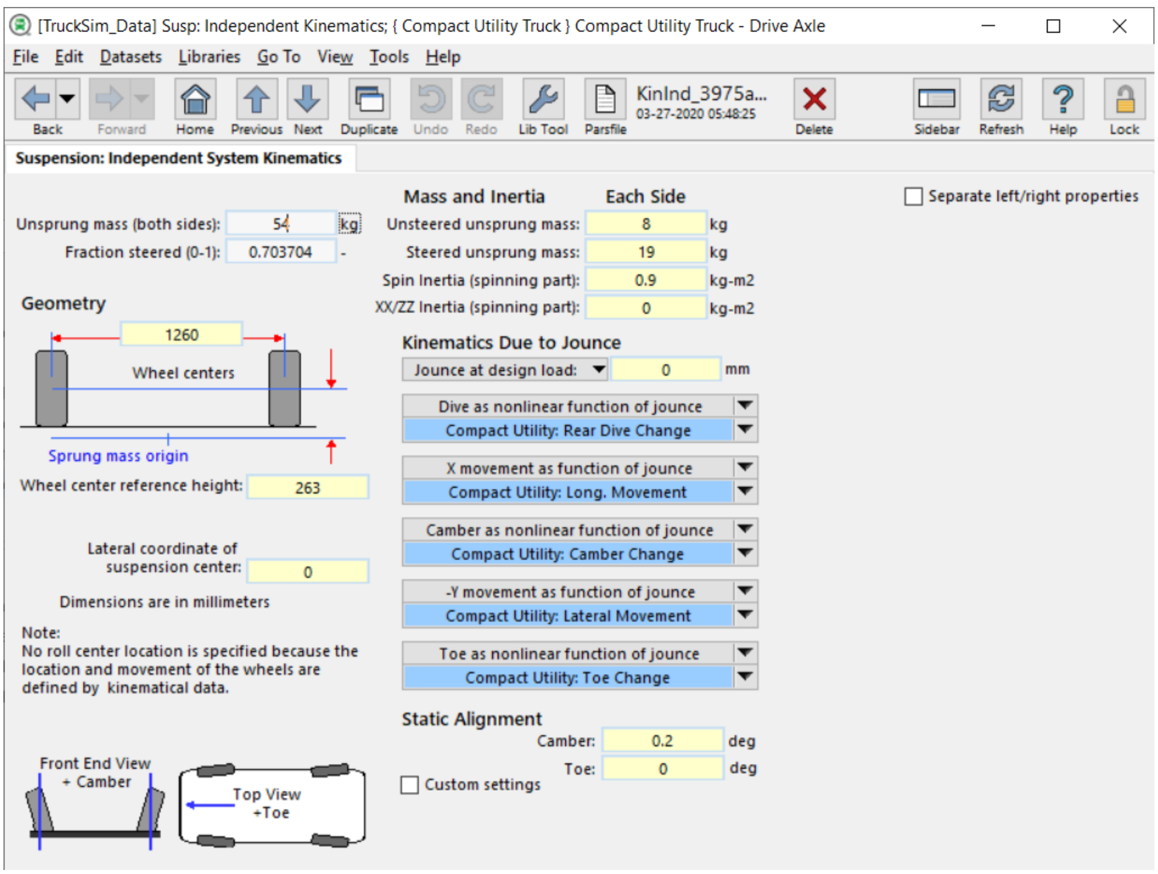

Figure 2. The **Susp: Independent Kinematics** *screen relates motions to Jounce*

Of special note is the pulldown control labeled “Kinematics Due to Jounce” (Figure 3).

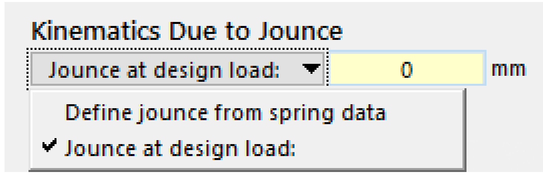

Figure 3. Two options to define zero jounce.

This pulldown allows you to choose how the value of jounce is assigned at any load.

The second choice is more commonly used. “Jounce at design load” allows you to specify a numerical value assigned to the definition of jounce when the wheels are at the location of the Wheel Center Height shown on the sprung mass screen.

Most often, jounce at design load is set to zero, so zero jounce corresponds to the Design Load condition. In some cases, other values might be used. Consider, for example, if you want to simulate a vehicle lifted by 20 mm, perhaps to provide clearance for larger tires, but the suspension is unchanged (hard points, control arm dimensions, etc.) You would adjust the wheel center height *downward* by 20 mm (raising the car means the wheels are farther away from the sprung mass, or lower in the sprung mass reference frame) and change the Jounce at Design Load to -20 mm, to indicate that the suspension has been extended (rebounded) by 20mm.

The first choice on the pulldown “Define jounce from spring data” is a bit more complicated. This option tells TruckSim to find the value for the spring compression at the design load (considering any mechanical ratio for the suspension) and use that spring compression and the mechanical ratio to obtain a number to be set as the value of jounce at the design load.

The “Define jounce from spring data” option is used almost exclusively when the suspension wheel rate is used for the spring properties, so the mechanical ratio is 1. This means jounce and spring compression have the same value.

It is critical to make the data consistent with the measurement method. If for example, “Define jounce from spring data” is chosen but the spring data is perhaps from a bench test where zero load occurs at zero compression and the suspension kinematics are from a K&C test (or simulation defining zero jounce at the Design Load, then the value of jounce at Design Load could be a large number (millimeters of spring deflection to obtain the design spring load). This would cause the values returned from lookup tables to be far from correct, and the vehicle simulation will produce incorrect results.

Trailers

Trailers are treated in a nearly identical manner to lead units. Each trailer has a Design Load Configuration nd a reference coordinate system. The Design Load doesn’t consider effects of payloads or anything about the vehicle to which the trailer is hitched. The key difference is that the body origin is located at the X coordinate of the hitch at the front of the trailer. The hitch has a height, as do the CG and wheel centers.

Do Reality Checks

When assembling a vehicle dataset for the first time, you should run some simple tests to be certain the vehicle behaves as you intend. A simple run with the vehicle at near-zero initial speed, zero open loop throttle, zero open loop braking, zero open loop steer, on a flat, level surface with no wind are best.

Check the tire vertical loads. Do they add up to the weight of the vehicle you expect? Don't overlook the hitch loads if a trailer is present.

Check the Z coordinates for the sprung mass CG and the sprung mass origin. Do these look correct?

Check the pitch and roll angles. They probably won't be zero, but do you understand the reasons?

If the weight distribution is not 50/50, the tires at the front will compress by different amounts from the rear. If the vehicle has a powertrain and is not in neutral, the drive torques at the wheels are reacted at the sprung mass, causing longitudinal load transfer. If the vehicle also has a solid axle, the powertrain might produce a roll reaction at the driveshaft.

If the suspensions have static camber and toe, the lateral force reaction in the suspensions can cause jacking up or down, changing the attitude of the vehicle.

If the suspension has friction, and the suspension changes compression at all during settling to equilibrium (and it will), the friction adds to the spring force and can cause jounce to be higher or lower than without friction.

Look at the wheel center Z coordinates. Do they differ from the wheel center heights you entered? In general, they do. Do you understand why? (Hints: Sprung mass origin above or below ground, tire compression, load distribution, minor load transfer effects.)

Check suspension jounce and spring compression output variables. Compare the results to the tables in your dataset. Are the values what you expect? Is the vehicle operating in the right part of the table for the conditions? If it isn't, things like roll center and pitch center will be wrong, and vehicle dynamics will be incorrect.

Check the output variables for jounce and rebound stop forces. Incorrect specifications may involve these components when they shouldn't be.

How is the vehicle speed changing? Are the brakes producing torque when perhaps they shouldn't? (Check the tables for correctness). Is the powertrain torque consistent with the vehicle idling? Is it in the correct gear?

Does the vehicle go straight? If it doesn't, what are the sources of asymmetry? Are they what you intend?

Remember: You are responsible for ensuring that you have modeled the vehicle in a way that is adequate for your needs, or the needs of whoever you will deliver the dataset to. Most correlation issues (by far!) result from poorly specified parameters.

Case Study: Parameters Influencing Equilibrium

The TruckSim 2020.1 example database includes a run in the category "* TS 2020.1 - K & C Tests" titled "K & C: Design Load Condition".

Review the linked Procedure and the "K&C Rig for Design Load Condition" dataset linked to the procedure to see how it was implemented.

In this run, user-defined custom forces and VS Commands are used to simulate the clamps that position a sprung mass on a suspension parameter measurement machine. One clamp is located at the X and Y location of each wheel (wheelbase and track width) of the vehicle being measured. The clamps are at a Z coordinate of zero in the sprung mass, and the VS Commands clamp them to a point at a Z of zero in global coordinates. This forces the sprung mass to be at zero Z, zero pitch and zero roll.

VS Commands and import variables are used to override the Z coordinate of the ground under each tire. The coordinate of the ground is changed using a simple proportional control minimizing the error between the current wheel center height at each wheel and the specified wheel center height at Design Load Condition. The ground under each wheel is moved until the wheel center height is within a user-specified error to the specified value.

Several Plot Setups are linked to display results for data relevant to this discussion.

Using the Example

With the example database as installed, navigate to the run mentioned above and use the View button to open the Echo File with Initial Conditions. Click the Plot button to open the plots and drag the time slider control to the far right, the end of the run. Also, one by one, click the mouse in each plot and type "v" to display the values for each plotted variable in the legend.

First, locate the plots for "Sprung Mass Origin Vertical Position", "Pitch Angle of Sprung Masses vs Time" and "Roll Angle of Sprung Masses vs Time". Observe their values appear to be negligibly small. Also, locate the plot for "Z Coord.: Wheel Centers". See that their values agree with the Wheel Center Heights at Deign Load specified on the Vehicle Sprung Mass screen.

These observations confirm that the vehicle has been placed in the Design Load Condition.

Look at vertical forces at each wheel (the first plot displayed). Also, in the Echo File, scroll down to the "SUSPENSION SPRINGS AND DAMPERS" section. In that section, you will note several commented-out items with the word CALC in their descriptions. Locate the calculated parameters called FZ_STATIC(1,1) and FZ_STATIC(1,2). These are the total loads at the ground calculated from the vehicle parameters for the front wheels used to initialize the run. FZ_STATIC(2,1) and FZ_STATIC(2,2) are the total loads at the ground calculated from the vehicle parameters for the rear wheels. Simple algebraic assumptions are used to obtain them. If the vehicle had one or more payloads, their weight would be included. For this run there are no payloads so we can reproduce the assumptions of the Design Load Condition.

Return to the plots. Look at the plot of Vertical Forces. These are the vertical forces at each wheel. Note that the front forces differ from the Echo File values significantly, and the rears by an even larger amount. So, which one is "right"? Both.

Consider the results in the Echo File to be similar to the hand-calculated sort of things found in textbooks. Here, they are used for one purpose: to obtain initial values for many aspects of a simulation.

The plotted values at the end of the run include the full model detail, and result from the integration of differential equations, and involve a simple controller with gains and tolerances.

We also see differences between the values of FS_STATIC() listed in the Echo File and the values for spring forces in the plots.

The position of the sprung mass and wheel verifies the vehicle in Design Load Condition, so can these differences be accounted for?

Resolving Differences - Forces

In the VS Browser for this example, navigate to the Front Suspension **Solid Axle Compliance** screen. Observe that the Springs are set to have Friction equal to 2000 N. Friction in a system depends on the history of motion or loads, and at initialization no history exists, so it can't be considered in the Design Load Condition. In the simulation, the ground is moved (with resulting small suspension movement) to place the sprung mass and wheels in the desired orientation, so friction has been present. So part of the spring force is friction; it's not entirely derived from the spring rate.

Navigate to the rear suspension. It also has friction of 5000 N per spring.

Return to the Run Control screen and create a new run. Follow the methods described in the Quick Start guide to make a duplicate vehicle for the new run, and on the vehicle make duplicate **Solid Axle Compliance** datasets for the front and rear suspensions. On these, set the spring friction to zero.

Return to the Run Control screen and make the run. As before, open the Echo File with Initial conditions and the Plotter.

We now see that the rear wheel and spring forces match the Echo File initial estimates, but the front forces show slight asymmetry. What could account for this?

Resolving Differences - Kinematics

We make two observations: One, the asymmetry of load occurs only at the front suspension, with the wheel centers at the same height. The height of the ground under the left and right front wheels shows a slight difference, indicating different amounts of tire compression to achieve the wheel center positions. And two, although there are no model parameters that are intentionally asymmetric, the TruckSim steering system is inherently so. This leads us to examine steer effects.

Examining the plot of road wheel steer angles shows a slight steer angle at the right front wheel.

Navigate to the Steering system screen linked to the vehicle you just made. Duplicate (Copy and Link) the steering system dataset. Go to the dataset and examine it. We are looking for something that could cause a steer angle at equilibrium. Observe the kingpin geometry specifications. Consider for a moment the effects of an inclined steer axis with significant offset from the wheel center. When the wheel is steered about this inclined axis, the path followed by the wheel center is "tipped" like the steer axis, so steering will raise or lower the wheel center slightly.

Although the inclined steer axis produces a kingpin moment at each wheel, the two wheels are connected to each other by a tie rod, so the moments should balance. Axle wrap causes steer, but jounce is zero so wrap effects are zero.

Note the parameter for “tie rod compliance”. According to the description, this compliance produces steer at the right wheel in proportion to the right wheel kingpin moment. It represents steer resulting from small deflections of the tie rod and its joints. Since it affects only the right wheel, it is a source of asymmetry.

On the steering system data set you just made, set the parameter for tie rod compliance to zero

Return to the Run Control screen, make the run, and compare the values for tire and spring forces to the Echo File as before.

They are now in agreement, and the right front steer angle is also zero.

The Final Word

The Design Load Condition defines a coordinate system for the vehicle, allowing us to know its position and orientation, and specifies critical relationships between vehicle systems and components. If you fail to define vehicle properties correctly, your simulations will be inaccurate.

The Design Load Condition involves only a few parameters. It is used only to set up the critical relationships between parts and systems, and to estimate the initial state of the vehicle. Nearly all outputs of a simulation depend on the correct specifications of these things.

To place the vehicle exactly in the Design Load Condition in a simulation requires some work, as it does not typically define an equilibrium state. It also requires a thorough understanding of the meaning of Design Load Condition and of the ways other systems contribute to the equilibrium state.

In physical tests such as Kinematics and Compliance tests, engineers take pains to position the vehicle precisely, attempting to remove effects of friction, and matching the orientation for which the mass has been defined.

Many other properties in these simulations can have effects like those illustrated. Any asymmetry, friction, dual tires, static camber and toe, the kinematics tables, compliances, and other details can introduce such differences.

This brief study does not represent a comprehensive list of vehicle properties that can cause the equilibrium state to differ from the Design Load Condition, nor is that its intent. Its purpose is to point out ways that subtle interactions of many properties combine to influence the equilibrium state. When such effects are observed, the model is not “wrong,” nor do they result from things like round off. Careful study can always identify the sources, and help you understand how parameters affect the vehicle’s behavior.

Good simulation requires good and correct data.