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Powertrain System

Every vehicle model in CarSim or TruckSim has some sort of means for powering the vehicle. The top-level powertrain settings are listed in the Echo file, such as the example for a TruckSim combination vehicle shown in Figure 1.

The first parameter, `POWERTRAIN_UNIT`, exists for combination vehicles and specifies which vehicle unit is powered. The default is unit 1, which is the case for nearly all examples in CarSim and TruckSim.

The second item is a combination of a command and parameter. `INSTALL_POWERTRAIN` is a command that install a powertrain with a specified type, ranging from 0 (simple drive provided by the built-in speed controller), through various numbers of drive axles (2 in CarSim, and up to 5 in TruckSim). When applied, it creates many internal variables that are specific to the selected type. Trying to change the type would cause conflicts, so the command can only be applied once with a non-zero type.

```
!------------------------------------------------------------------------------------
! POWERTRAIN
!------------------------------------------------------------------------------------
! The powertrain model is specified with the following parameters along with up to
! 25 nonlinear Configurable Functions. Open-loop throttle can be specified with the
! function THROTTLE_ENGINE. Engine behavior is specified in part with the functions
! MENGINE and FUEL_RATE.

POWERTRAIN_UNIT      1 ! Vehicle unit with powertrain
INSTALL_POWERTRAIN   2 ! Powertrain type: 0 -> Simple, 1 -> front-axle drive, 2 ->
                       ! rear-axle drive, 3 -> 2-axle drive, 4 -> 3-axle drive, 5 ->
                       ! 4-axle drive, 6 -> 5-axle drive, 7->AVL Cruise [L]
! R_DRIVE_SC(1)      0 ; - ! Drive torque ratio: [this axle]/[total] [I]
! R_DRIVE_SC(2)      1 ; - ! Drive torque ratio: [this axle]/[total] [I]
OPT_HEV              0 ! Propulsion types: 0 -> internal-combustion engine, 1 ->
                       ! power-split hybrid electric, 2 -> electric, 3 ->
                       ! range-extended electric (series hybrid), 4 -> parallel
                       ! hybrid electric
```

Figure 1. Powertrain section of a TruckSim Echo file for vehicle with rear-axle drive.

The built-in speed controller always uses drive torque ratios (`R_DRIVE_SC` in TruckSim, and `R_DRIVE_REAR` in CarSim) to convert target forward speed to wheel speed, and to convert target forward acceleration to wheel torque. The number of available types depends on the number of axles that could potentially be driven.

`OPT_HEV` is another combination command and parameter: it determines whether the powertrain uses electric or hybrid components. It also cannot be changed after it is set to anything but zero.

Connecting a Powertrain to the Vehicle

In most cases, the powertrain drives some or all the wheels a car or truck, or the lead unit of a combination vehicle. TruckSim includes six libraries of powertrain configurations (up to 10 x 10), and CarSim includes three libraries.

The number of powered axles determines which powertrain library is used to connect a powertrain dataset.

In CarSim, the Vehicle Assembly screen has a drop-down list (Figure 2) for specifying the type of powertrain.

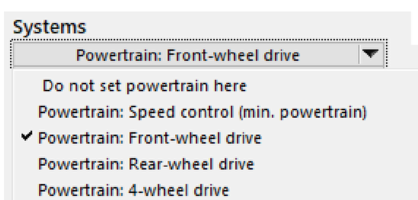

Figure 2. Drop-down control to specify how axles are powered.

The first option is used in case the powertrain is applied to a trailing unit, rather than the lead unit in a combination vehicle.

The second item creates a minimal powertrain that can be used to control the speed of the vehicle (Figure 3) when information is not easily obtained for a full powertrain model. In this case there are just two parameters: `PMAX_SC` and `R_REAR_SC`.

```
!--------------------------------------------------------------------------------
! POWERTRAIN
!--------------------------------------------------------------------------------
INSTALL_POWERTRAIN  0 ! Powertrain type: 0 -> Simple, 1 -> FWD, 2 -> RWD, 3 -> AWD
                      ! [L]
PMAX_SC           201 ; kW ! Maximum power available with simple PT [I]
R_REAR_DRIVE_SC     0 ; - ! Drive torque ratio: [rear axle]/[total] [I]
```

Figure 3. Powertrain section of the CarSim Echo file with the minimal option.

The next three options in the list (Figure 2) connect with libraries for Front-wheel drive, Rear-wheel drive, and 4-wheel drive.

TruckSim has six libraries for lead units with one to five drive axles. Screens for each of these libraries have a similar drop-down list. For example, Figure 4 shows the options available for a five-axle lead unit in TruckSim.

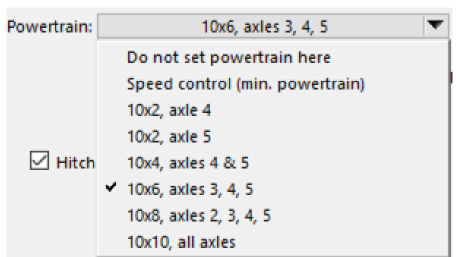

Figure 4. Powertrain options for 5-axle lead unit in TruckSim.

In the rare occasions where the powertrain will be applied to a trailer, rather than the lead unit, three settings are needed:

1. Make sure the lead unit does not set the powertrain: select the first option from the powertrain menu in CarSim (Figure 2) or TruckSim (Figure 4).
2. Using a Miscellaneous field in the **Combination Vehicle** screen in TruckSim or the **Vehicle with Loads, Sensors, Trailers**, **etc**. screen in CarSim, set `POWERTRAIN_UNIT` to the unit number of the trailer (e.g., 2).
3. Using a Miscellaneous link in the **Combination Vehicle** screen in TruckSim or the **Vehicle with Loads, Sensors, Trailers**, **etc**. screen in CarSim, link to a Powertrain dataset of choice. The number of drive axles in the selected dataset must not exceed the number of axles on the trailer. (For a 1-axle trailer, select a **Powertrain: Rear-Wheel Drive** dataset.)

Assembling Powertrain Components

A conventional powertrain in CarSim or TruckSim includes an internal combustion engine, torque transfer device (torque converter or mechanical clutch), transmission, transfer case (for 4WD), and differential gears on the front and rear axles (Figure 5).

The inputs from the driver or other speed controller involve the throttle, gearing from the transmission, and possibly clutch and shifting inputs.

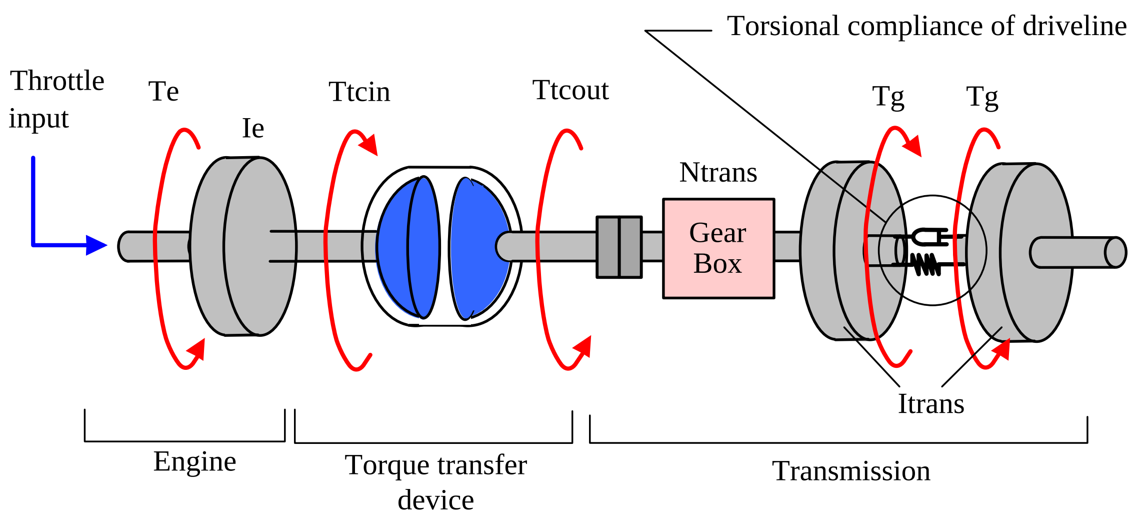

Figure 5. Torques between engine, torque transfer device, and transmission.

With front-wheel drive (FWD) or rear-wheel drive (RWD), the transmission output is fed to the differential gear, which is in the middle of the drive axle. Figure 6 shows a diagram for the rear axle and differential gear in a RWD system.

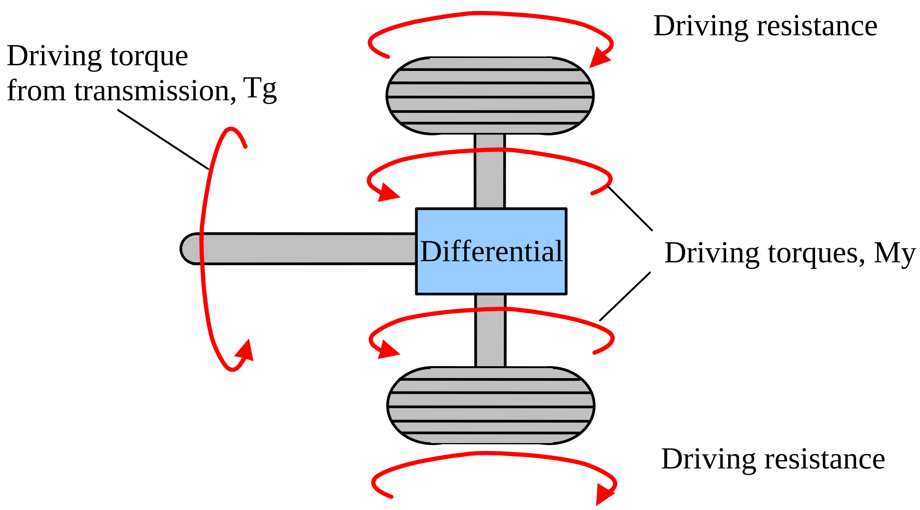

Figure 6. Differential at rear drive axle (rear-wheel drive vehicle).

In the 4-wheel drive system (4WD) shown in Figure 7, the transmission output is fed to the transfer case, which is in between the front and rear drive shafts that connect with the front and rear differentials, respectively.

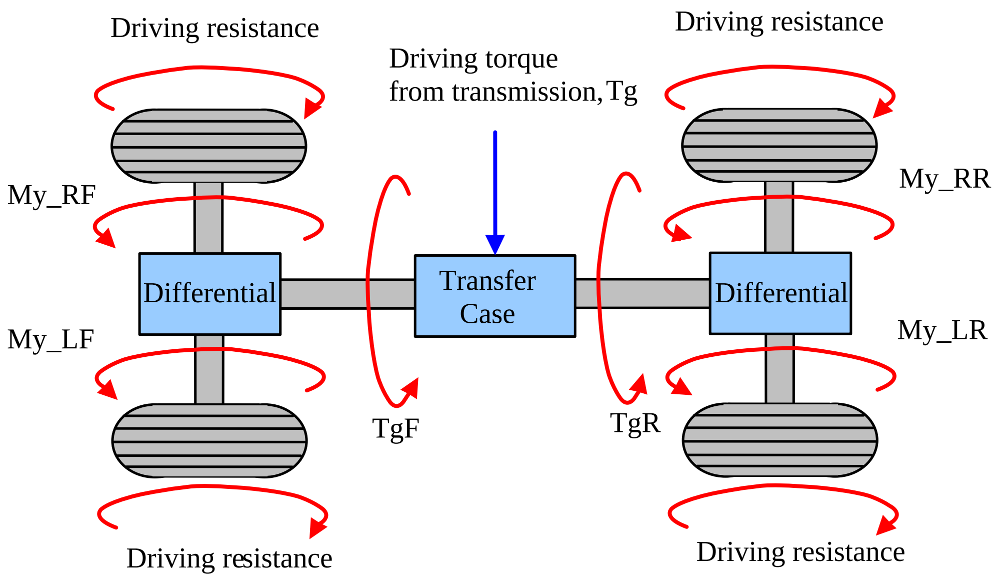

Figure 7. Transfer case and differentials (four-wheel drive vehicle).

This document is the main source of information for how the conventional powertrain model is set up and used. However, two other Help documents cover other aspects of the powertrain model and its use:

- *Driver Controls* describes how inputs to the powertrain may be provided as open-loop functions of time, or using target speed, or acceleration with the closed-loop speed controller (SC) included in CarSim and TruckSim. This document also covers the closed-loop clutch and throttle modulation used for shifting with a clutch automatically.
- *Powertrain for Electric and Hybrid Electric Vehicles (BEV/HEV)* describes the powertrain options for electric and hybrid vehicles.

Organization of Powertrain Settings in an Echo File

The minimal information for a powertrain was shown in Figure 3 (page 3), with just two parameters that can be used by the closed-loop speed controller. With a full powertrain, parameters and Configurable Function datasets are shown in several sections:

- **Powertrain**: the first section has the title `POWERTRAIN` (Figure 8) and defines the general type of powertrain and connections to the driver wheels. The contents of this section include system-level parameters and commands, followed by parameters associated with differentials. If the vehicle has electric motors, they are also specified. As mentioned earlier, the number of drive axles is set with the command `INSTALL_POWERTRAIN` (line 540). The information shown in this section is provided from the VS Browser and database from the top-level powertrain library and some of the links to differential datasets. Note that this command is locked after the run starts, as indicated by the suffix [L] in the description. Once the type has been set, it cannot be changed.

```
533 !------------------------------------------------------------------------------------
534 ! POWERTRAIN
535 !------------------------------------------------------------------------------------
536 ! The powertrain model is specified with the following parameters along with up to
537 ! 25 nonlinear Configurable Functions. Open-loop throttle request can be specified
538 ! with the function THROTTLE_ENGINE.
539
540 INSTALL_POWERTRAIN  1 ! Powertrain type: 0 -> Simple, 1 -> FWD, 2 -> RWD, 3 -> AWD
541                       ! [L]
542 ! R_REAR_DRIVE_SC   0 ; - ! Drive torque ratio: [rear axle]/[total] [I]
543 OPT_HEV             0 ! Propulsion types: 0 -> internal-combustion engine, 1 ->
544                       ! power-split hybrid electric, 2 -> electric, 3 ->
545                       ! range-extended electric (series hybrid), 4 -> parallel
546                       ! hybrid electric
547 OPT_THROTTLE_DELAY  0 ! Apply lag to requested throttle using time constants: 0 ->
548                       ! no, 1 -> yes
549 VLOW_IW             0 ; km/h ! [D] Increase wheel spin inertia below this speed to
550                       ! fix instability with some HIL systems; set 0 to disable
551
552 ! The powertrain differentials are specified with the following parameters and the
553 ! function M_DIFF_VISC.
554
555 ! NDIFF             1 ! Maximum number of differentials that can exist in this
556                       ! powertrain (read only)
557 OPT_DIFF_INTERNAL(1) 1 ! Front diff model: 1 -> internal, 0 -> external [I]
558 OPT_LOCKED_DIFF(1)  0 ! Is the front diff locked? 0 -> no, 1 -> yes [I]
559 LOCKED_DIFF_DAMP(1) 1 ; N-m-s/deg ! Torsional damping for locked front diff [I]
560 LOCKED_DIFF_K(1)  100 ; N-m/deg ! Torsional spring rate for locked front diff [I]
561 R_EFF_F_DIFF(1)  0.99 ; - ! Forward efficiency of front diff [I]
562 R_EFF_R_DIFF(1)  0.99 ; - ! Reverse efficiency of front diff [I]
563 R_GEAR_DIFF(1)    4.1 ; - ! Gear ratio of front diff [I]
564 IDS(1)          0.013 ; kg-m2 ! Spin inertia of front diff input shaft [I]
565 IHS_L(1)        0.009 ; kg-m2 ! Spin inertia of left half shaft, front diff [I]
566 IHS_R(1)        0.009 ; kg-m2 ! Spin inertia of right half shaft, front diff [I]
567 OPT_CLUTCH_DIFF(1)  0 ! [D] Clutch control for front diff: 0 -> table lookup or
568                       ! external, 1 -> Torsen parameters, 2 -> yaw control. When 0
569                       ! or 2, functions CLUTCH_CON_DIFF and CLUTCH_TORQUE_DIFF are
570                       ! used. When 2, CLUTCH_TORQUE_DIFF2 is also used. [I]
571 OPT_TWIN_CLUTCH(1)  0 ! [D] Twin clutches on front diff? 0 -> no, 1 -> yes. If 1,
572                       ! then functions CLUTCH_TWIN and M_TWIN are used. [I]
573
```

Figure 8. Powertrain section of Echo file.

> **Note** Parameters for electric motors and hybrid setups are described in the companion Help document, *Powertrain for Electric and Hybrid Electric Vehicles (BEV/HEV)*.

- **Engine**: the next section, with the title `ENGINE` (Figure 9), appears if the powertrain includes an internal combustion engine. In this case, the engine is installed with the command `INSTALL_ENGINE` (line 580). This command is mandatory if the settings in the Powertrain section require an internal combustion engine; an error message is generated if this command is not provided for a powertrain type that involves an internal combustion engine.
- **Torque Transfer Device**: the next section, with the title `TORQUE TRANSFER DEVICE` (Figure 10), appears if the powertrain includes an engine (and necessarily a transmission). In this case, the transfer device is installed with the command `INSTALL_TORQUE_TRANSFER_DEVICE` (line 598). This command is mandatory if the settings in the Powertrain section require an engine.

```
!--------------------------------------------------------------------------------
! ENGINE
!--------------------------------------------------------------------------------
! Behavior of an internal-combustion engine is specified with the Configurable
! Functions MENGINE and FUEL_RATE, along with the following parameters.

INSTALL_ENGINE          ! VS Command to install an engine

OPT_ENGINE_INTERNAL 1 ! Engine model: 1 -> internal, 0 -> external [I]
OPT_ENGINE_RUNNING  1 ! [D] Is engine running? 1 -> yes, 0 -> no
AV_ENG_IDLE       750 ; rpm ! Engine idle speed [I]
ENGINE_ESC_PG       5 ; 1/s ! [D] P gain of ESC engine torque control
ENGINE_ESC_IG     0.5 ; 1/s2 ! [D] I gain of ESC engine torque control
ENGINE_STALL_DAMP 0.2 ; N-m-s/deg ! [D] Damping rate of the stalled engine
IENG             0.16 ; kg-m2 ! Spin inertia of engine crankshaft [I]
ITC_INPUT_SHAFT 0.015 ; kg-m2 ! Spin inertia of input shaft of torque converter

```

Figure 9. Engine section of Echo file.

```
!--------------------------------------------------------------------------------
! TORQUE TRANSFER DEVICE
!--------------------------------------------------------------------------------
! Transfer of power from the engine to the transmission is specified with the
! following parameters to specify a hyraulic torque converted or a mechanical
! clutch.

INSTALL_TORQUE_TRANSFER_DEVICE  ! VS Command to install a clutch or torque converter

OPT_CLUTCH          0 ! [D] Torque transfer to transmission: 0 -> hydraulic torque
                      ! converter, 1 -> mechanical clutch, 2 -> torque converter
                      ! with lock-up clutch, 3 -> centrifugal clutch. The torque
                      ! converter options (0 and 2) use functions INV_CAP_TC and
                      ! RM_TC. Option 2 also uses LOCK_AT and UNLOCK_AT. [I]
OPT_PWR_CPL_INTERNAL 1 ! Internal power coupling model (torque converter and
                       ! clutch): 1 -> internal, 0 -> external

```

Figure 10. Torque Transfer Device section of Echo file.

- **Transmission**: the next section, with the title `TRANSMISSION` (Figure 11), appears if the powertrain includes an engine. In this case, the transfer device is installed with the command `INSTALL_TRANSMISSION` (line 616). This command is mandatory if the settings in the Powertrain section require an engine. This section also includes parameters for gear shifting. The shifting might be automatic (if there is a hydraulic torque converter, or if a clutch is used with an internal closed-loop control for clutch and throttle based on shifting).

Top-Level Powertrain Screens

As mentioned earlier, CarSim has three libraries (front-, rear-, and all-wheel drive) for the built-in powertrain options. TruckSim has six libraries of powertrain configurations.

Figure 15 (page 10) shows the screen that assembles the information needed to define a four-wheel drive powertrain – power source 1, torque converter (or clutch) 4, transmission 6, transfer case 8, and differentials (10 and 12). Each part can be switched between the internal model and an external model by using a drop-down list (e.g., the drop-down list of internal-combustion engine model options, Figure 12).

```
!-------------------------------------------------------------------------------
! TRANSMISSION
!-------------------------------------------------------------------------------
! The transmission is specified with the following parameters and Configurable
! Functions noted below. Transmission controller mode can be specified with the
! open-loop function MODE_TRANS and transmission gear can be specified with the
! open-loop function GEAR_TRANS.

INSTALL_TRANSMISSION  ! VS Command to install a transmission

OPT_TRANS_INTERNAL  1 ! Transmission model: 1 -> internal, 0 -> external [I]
OPT_TR_GEAR_INTERNAL 1 ! Transmission gear ratio and inertia: 1 -> up to 18 gears, 2
                       ! -> continuously variable (CVT), 0 -> external model.
                       ! Option 1 uses functions DOWNSHIFT_TRANS and UPSHIFT_TRANS.
                       ! Option 2 uses functions R_GEAR_CVT, R_EFF_CVT_F, and
                       ! R_EFF_CVT_R. [I]
LIMIT_DOWNSHIFT     1 ! [D] Limit to number of gears covered in a downshift
LIMIT_UPSHIFT       1 ! [D] Limit to number of gears covered in an uphift
NGEARS              6 ! Number of forward gears in transmission [I]
OPT_SHIFT_INTERNAL  1 ! Gear shift command model: 1 -> internal, 0 -> external [I]

DRIVELINE_FREQ      9 ; Hz ! Natural frequency of entire driveline, including
                      ! transmission, differentials, and wheels, but not including
                      ! the engine. Does not include effect of nonlinear function
                      ! M_TRANS_ROT. [I]
DRIVELINE_ZETA    0.9 ; - ! Damping ratio of entire driveline. Does not include
                      ! effect of nonlinear function M_TRANS_AV. [I]
ITC_OUTPUT_SHAFT 0.015 ; kg-m2 ! Spin inertia of torque converter output shaft [I]
ITR_NEUTRAL      0.034 ; kg-m2 ! Neutral-gear spin inertia of transmission
ITR_REVERSE      0.034 ; kg-m2 ! Reverse-gear spin inertia of transmission
R_EFF_TR_F_REVERSE 0.9 ; - ! Reverse-gear forward efficiency of transmission
R_EFF_TR_R_REVERSE 0.9 ; - ! Reverse-gear reverse efficiency of transmission
R_GEAR_TR_REVERSE -3.168 ; - ! Reverse-gear ratio of trans (should be negative)
T_SHIFT           0.25 ; s ! Shift duration used in closed-loop transmission control
                      ! if upshift and/or downshift duration is not set for a gear

ITR(1)           0.037 ; kg-m2 ! 1st-gear transmission spin inertia at output shaft
                      ! (Transmission spin inertias do not include the torque
                      ! converter)
R_EFF_TR_F(1)     0.92 ; - ! 1st-gear forward efficiency of transmission
R_EFF_TR_R(1)     0.92 ; - ! 1st-gear reverse efficiency of transmission
R_GEAR_TR(1)     3.538 ; - ! 1st-gear ratio of transmission
T_SHIFT_DOWN(1)     -1 ; - ! [D] Duration of down-shift to 1st gear. If not specified
                      ! (default = -1), then T_SHIFT is the duration
T_SHIFT_UP(1)       -1 ; - ! [D] Duration of up-shift from 1st gear. If not specified
                      ! (default = -1), then T_SHIFT is the duration
```

Figure 11. Transmission section of Echo file.

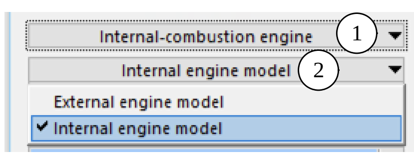

Figure 12. Drop-down list for engine type.

The block diagram on the screen shows the power flow from the engine to the wheels using red arrows. If an external model is selected, the internal model is completely ignored; this means that the power flow is completely routed through the external model, and the internal model does not pass any torque and physical state information (such as rotational angle and speed) to the next parts (Figure 13).

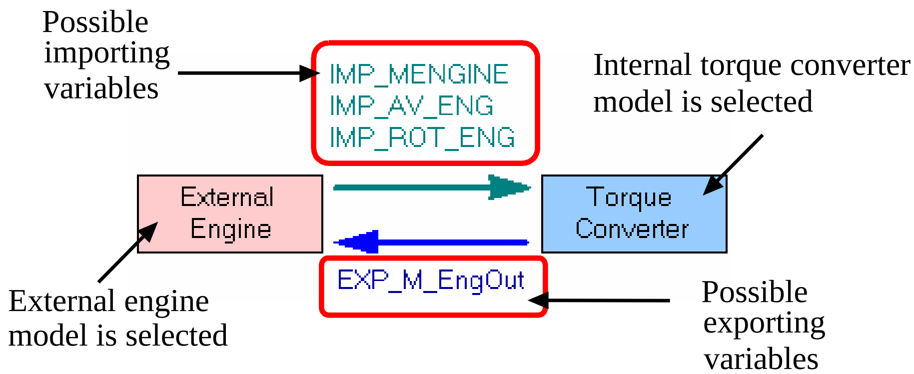

Figure 13. Diagram between the external and internal model blocks.

When an external model is selected for part of the system, you must feed power and physical state information from/to the next parts using the external import/export variables. In the block diagram on the screen, an external model is shown by a red block, and possible importing variables from the external model are shown by green and possible exporting variables to the external model are shown by blue. Those import/export variables are not set automatically; you need to set them using the **I/O Channels: Import** and **I/O Channels: Export** screens.

CarSim and TruckSim support three different propulsion systems. Select the type of system from the ring control 1 on the powertrain assemble screen (Figure 14):

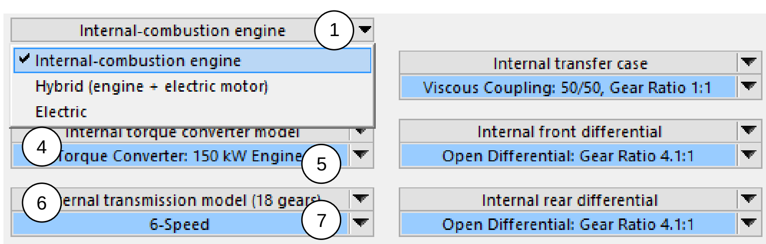

Figure 14. Select either internal-combustion, hybrid-electric or electric system.

1. **Internal-combustion engine**: an engine, a hydraulic torque converter (or mechanical clutch) and a transmission are connected in series,
2. **Hybrid (engine + electric motor)**: an engine, a generator and a motor are connected in parallel by a planetary gear whereas the motor shaft is the output to a differential (or transfer case), or
3. **Electric**: the power source is only an electric motor which outputs to a differential (or transfer case).

Selecting the menu item **Internal-combustion engine** (`OPT_HEV = 0`) installs conventional powertrain components such as the torque converter, clutch and transmission, without electric or hybrid components such as electric motor, generator, and planetary gear sets.

Selecting either the menu item **Hybrid (engine + electric motor)** or **Electric** installs the hybrid/electric components with the power management control (`OPT_HEV` = `1` for hybrid or `2` for electric) and two library links to the torque converter 5 and transmission 7 screens are replaced with the links for **Powertrain: Hybrid/Electric System** and **Hybrid/Electric Power Management control** libraries, respectively (external links 4 and 6 are hidden.)

If you select either Hybrid or Electric system, please see the separate document *Powertrain for Electric and Hybrid Electric Vehicles (BEV/HEV)* for further data settings.

Figure 15 shows the controls on a four-wheel drive powertrain screen. The numbered controls are described below.

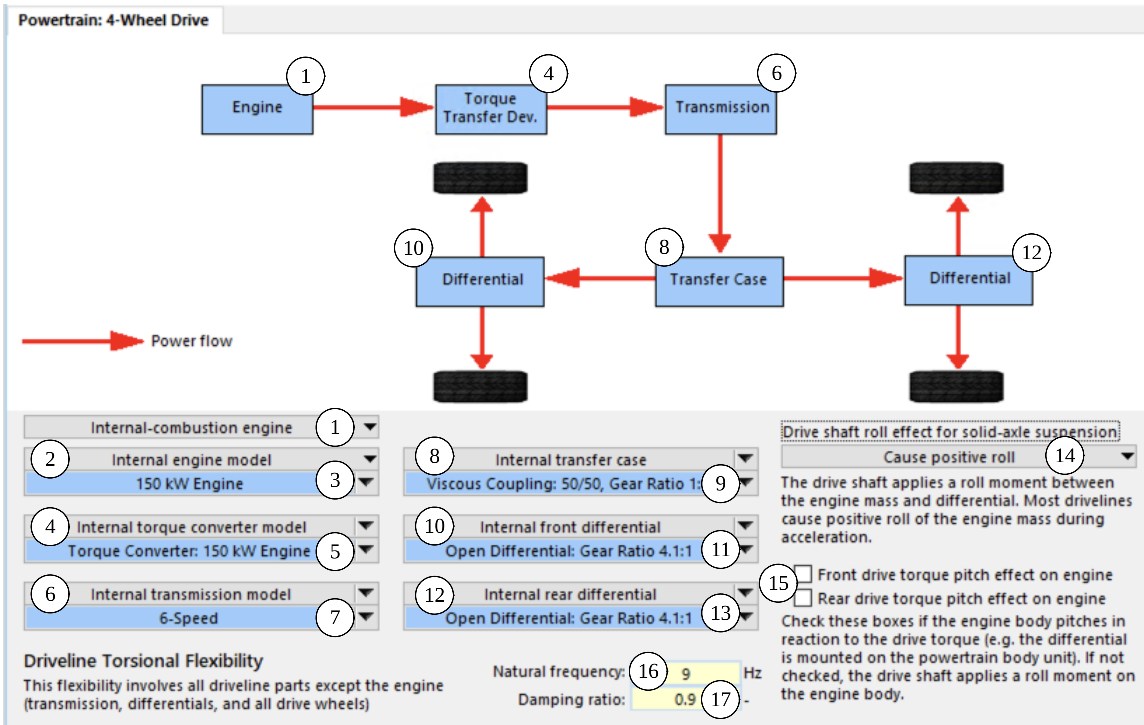

Figure 15. Powertrain assemble screen for four-wheel drive system.

Engine to transmission

1 Drop-down list of three source of power for the system (Figure 16).

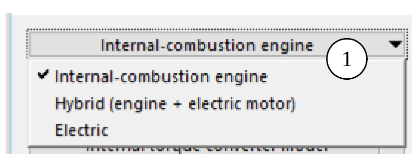

Figure 16. Three sources of power for the powertrain system.

This document covers the first option: internal-combustion engine. Information about the hybrid and fully electric options are described in the companion Help document, *Powertrain for Electric and Hybrid Electric Vehicles (BEV/HEV)*.

(2) Drop-down list (Figure 14, page 9) for selecting an external or internal engine model (keyword = `OPT_ENGINE_INTERNAL`). The data link for the engine (3) is hidden when the external engine model is selected.

(3) Link to a **Powertrain: Engine** dataset.

(4) Drop-down list for selecting an external torque coupling model, internal torque converter or internal clutch model (keyword = `OPT_PWR_CPL_INTERNAL`). The data link for the torque coupling (5) is hidden when the external torque coupling model is selected.

(5) Link to either a **Powertrain: Torque Converter** dataset or a **Powertrain: Clutch Torque** dataset. The type of link determines how the engine transfers torque to the transmission.

(6) Drop-down list for selecting an external or internal transmission model (keyword = `OPT_TRANS_INTERNAL`).

(7) Link to either a **Powertrain: Transmission (External)** dataset or a **Powertrain: Transmission** dataset.

Differentials

(8) Drop-down list for selecting an external or internal transfer case model (keyword = `OPT_DIFF_INTERNAL(3)`). The data link for the transfer case (9) is hidden when the external transfer case model is selected.

(9) Link to a **Powertrain: Transfer Case** dataset.

(10) Drop-down list for selecting an external differential, internal differential or internal twin-clutch differential model for the front axle (keyword = `OPT_DIFF_INTERNAL(1)`). The data link for the differential (11) is hidden when the external differential model is selected.

(11) Link to either a **Powertrain: Front Differential** dataset or **Powertrain: Front Twin-Clutch Differential** dataset. The type of link determines how the front drive shaft torque is transferred to the front wheels.

(12) Drop-down list for selecting an external differential, internal differential or internal twin-clutch differential model for the rear axle (keyword = `OPT_DIFF_INTERNAL(2)`). The data link for the differential (13) is hidden when the external differential model is selected.

(13) Link to either a **Powertrain: Rear Differential** dataset or **Powertrain: Rear Twin-Clutch Differential** dataset. The type of link determines how the rear drive shaft torque is transferred to the rear wheels.

Drive shaft reactions

The engine receives the torque reaction from the wheels through the drive shafts (pitch effect), or from the differentials through the propeller shafts (roll effect).

The ways to receive the torque reaction are defined by the drop-down list (14) and checkbox(es) (15) on the powertrain screens. However, those controls work differently depending on suspension types (either independent or solid axle suspension) and whether the optional engine mount model is in use.

1. In the case of the basic model (the engine mass is lumped as part of the sprung mass), the sprung mass receives the torque reaction from the differentials though the propeller shaft(s) in the roll direction when the powered axle is a solid-axle suspension (the differential is supposed to be mounted on the solid axle). The roll effect (clockwise or counterclockwise) is defined by the drop-down list ⑭. If the powered axle has an independent suspension, then the torque reaction defined by the drop-down list ⑭ is ignored because both the engine and differential are rigid parts of the sprung mass. In this case, the sprung mass receives the torque reaction from the wheels in the pitch direction no matter how the pitch effect checkboxes ⑮ are set. The checkboxes ⑮ are no effect on the basic model.

2. In the case of the engine-mount model, the engine mass is a separate body from the sprung mass, and it receives the torque reaction from the wheels through the drive shafts in the pitch direction, or from the differential(s) though the propeller shaft(s) in the roll direction. The direction of the reaction is depending on the pitch effect checkbox ⑮ for each powered axle. For example, in the four-wheel-drive system, either pitch or roll effect can be selected for each of the front and rear drive axles. If both pitch checkboxes are checked, the drop-down list for the roll effect ⑭ is hidden. Otherwise, the drop-down list is used to apply a roll effect for the front and/or rear axle that does not have a pitch effect. A drive axle cannot produce both pitch and roll effect simultaneously. Further mode, the solid More details about the engine mount model are described in the separate document, *Engine Mount Model*.

Drive shaft reaction settings

⑭ **Drive Shaft Roll Effect** pull-down control (keyword = `R_MDRIVE`). As described above, this setting causes the driveline to apply a moment between the engine and differential(s) during acceleration and deceleration with engine brake. Most engines and drivelines rotate counterclockwise when looking forward along the X axis, causing the engine to roll to the right (positive).

⑮ **Drive torque pitch effect** check box (keyword = `OPT_ENGINE_PITCH_REACTION`). If this checkbox is checked, the drive toque applies a moment between the drive wheels and engine mass during the acceleration and deceleration with engine brake. In this case, the engine body receives reaction torque in the pitch direction opposite of that applied to the wheels. For example, the engine body pitches in the negative direction (engine front up) during acceleration.

> **Note** Even though the basic model does not support the pitch effects, the roll effect drop-down list ⑭ is hidden in the GUI if all the pitch effect boxes ⑮ are checked. In this case, the clockwise roll effect (default) is applied if the basic model is used when the powered axle is the solid axle suspension.

Torsional Flexibility of Driveline

Generally, the driveline (from the transmission to drive axles including differentials and driveshafts) is not completely rigid and each part has some compliance due to torsional flexibility.

In the CarSim and TruckSim models, the flexibilities of all driveline parts are represented by a single torsional spring-damper, located after the transmission gearbox as shown in Figure 5 (page 4) and Figure 17, which shows the entire driveline for rear-wheel drive (RWD). The user input parameters for a natural frequency and damping ratio are converted automatically to the torsional stiffness and damping coefficient in the model and used for the simulation.

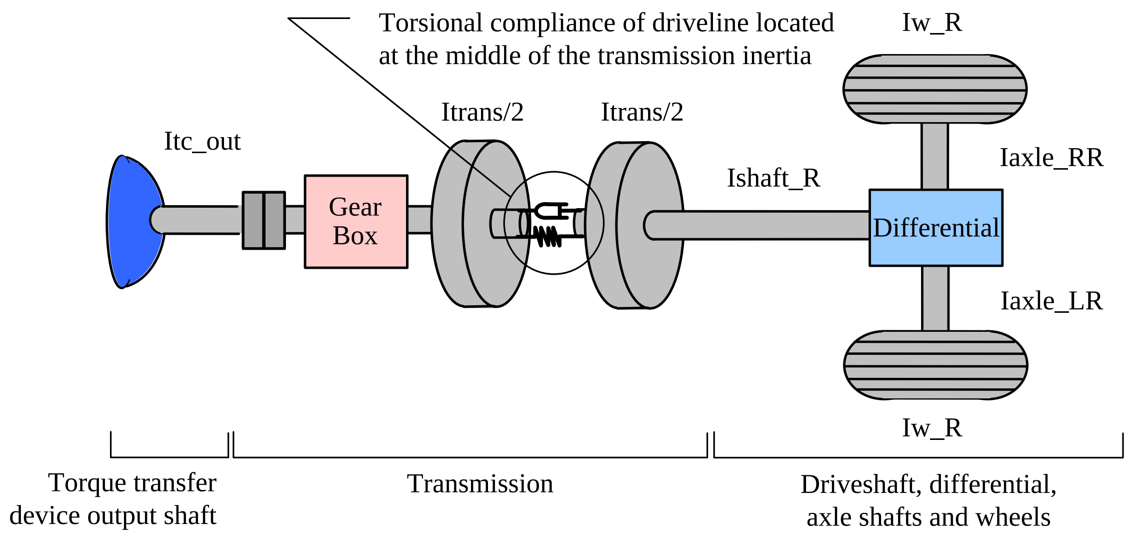

Figure 17. Entire driveline shown with a single unit of torsional spring-damper, which represents the torsional compliance of the driveline (RWD).

User settings (model parameters)

16 Natural frequency of driveline (keyword = `DRIVELINE_FREQ`).

17 Damping ratio of driveline (keyword = `DRIVELINE_ZETA`).

Note The torsional stiffness and damping coefficient derived from the user parameters (natural frequency and damping ratio) are linear. However, if you want to set non-linear characteristics, you can apply non-linear tables for the torsional stiffness and damping of the transmission. Those non-linear tables are available by using keywords: `M_TRANS_ROT` for stiffness and `M_TRANS_AV` for damping setting on the **Generic Table** screen. Those non-linear tables are added to $K_{driveline}$ and $D_{driveline}$, respectively, in the simulation. Therefore, if you use the non-linear tables, set zero for both natural frequency and damping ratio on the powertrain screen.

Measurement for user parameters

You can measure the torsional natural frequency and damping ratio of the driveline with the following method. First, the vehicle is lifted from the ground using a test rig. Make sure that the drive wheels are not touching the ground and there is no rolling resistance from the ground. Second, disconnect engine from the transmission. If the driveline involves a manual transmission, simply disengage the clutch. Third, apply either transient clunk impact [1] or randomly generated torque noise at the transmission input shaft. If it is difficult to apply the torque to the transmission input shaft, you may need to remove the entire driveline from the chassis. Another option is to apply the transient torque at all of drive axles. However, in this case, you must apply the exact same impact torque to all of drive axles. Then, measure torque and angular velocity of any part of driveline (the frequency and damping ratio should be the same everywhere in driveline.)

Validation in the simulation

Figure 18 shows examples of the power spectrum density of spectrum analysis results obtained by the VehicleSim vehicle model simulation. In this example, the natural frequency is set as 9 Hz and damping ratio is set to 0. In this simulation, the vehicle is lifted from the ground and the main clutch is disengaged. Random white noise torque is applied at the input shaft of the transmission. Angular velocities and torques at the transmission output shaft and drive wheel is measured. The vehicle has a rear-wheel drive powertrain. As shown in this figure, the natural frequency of the oscillation of torque and angular speed are same in the transmission and drive wheel – that is as same as the user input parameter of 9 Hz.

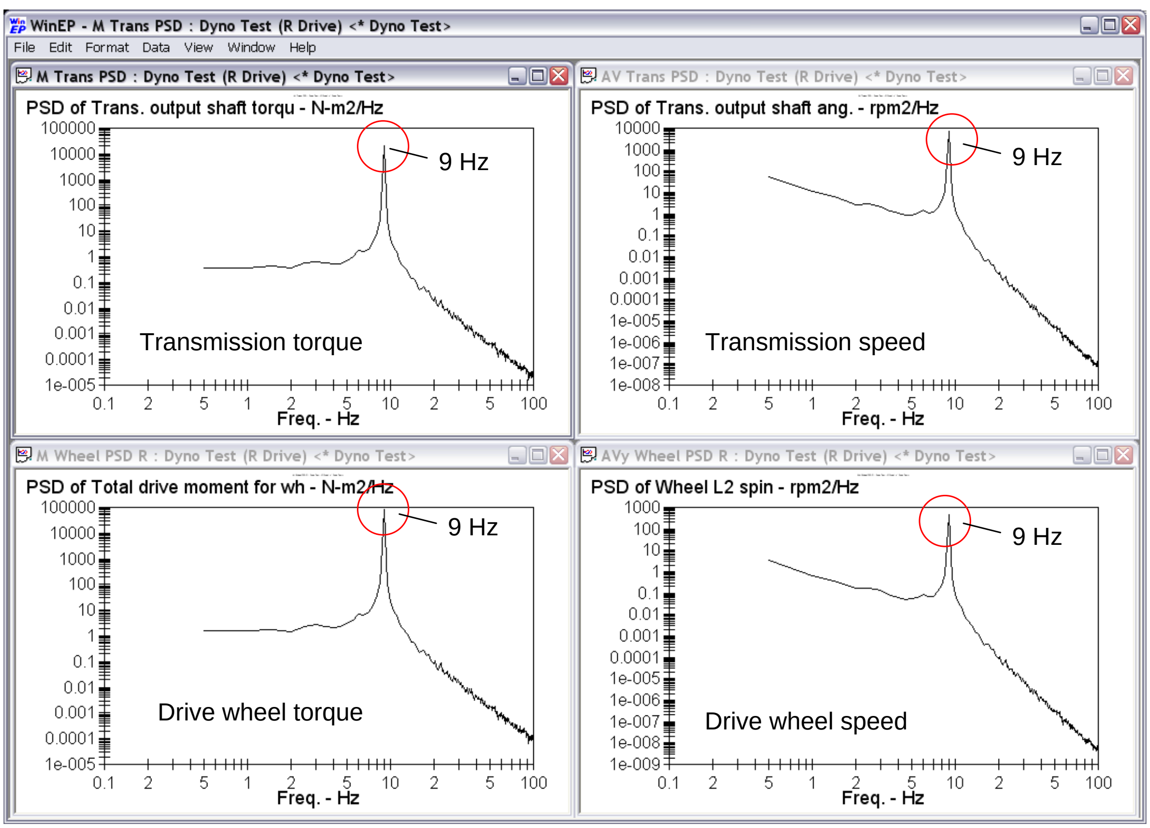

Figure 18. Driveline natural frequency obtained by VehicleSim vehicle model simulation (user input parameter for the natural frequency of the driveline is set as 9 Hz; damping ratio is 0).

Calculation of torsional stiffness and damping coefficient from model parameters

As described above, the torsional spring-damper is located after the transmission gearbox whose stiffness and damping coefficient are derived from the model parameters (natural frequency and damping ratio) and all driveline inertia by using the following equations.

The driveline can be split into two parts (engine side and wheel side separated at the middle of the transmission inertia where the torsional spring-damper is located, see Figure 17). First, both ends of driveline inertia are calculated. The front end of driveline inertia (engine side) is:

$$I_{driveline\_front\_end} = I_{tc\_out} \times N_{trans}{}^2 + 0.5 \times I_{trans} \tag{1}$$

The rear end of driveline inertia depends on what type of powertrain is used. If rear-wheel drive (RWD) is used, the rear end of driveline inertia is (also see Figure 17):

$$I_{driveline\_rear\_end} = 0.5 \times I_{trans} + I_{axle\_R} \tag{2}$$

where I_{axle_R} is rear driveshaft inertia involving the all inertia of both sides of drive axles and wheels such as:

$$I_{axle\_R} = I_{shaft\_R} + (2 \times I_{wR} + I_{axle\_LR} + I_{axle\_RR}) / N_{diff\_R}{}^2 \tag{3}$$

In case for the front-wheel drive (FWD), a similar calculation is applied. However, in the four-wheel drive (4WD), the rear end of driveline inertia should account the torque bias ratio of the central transfer case, $T_{bias\_to\_rear}$, such as:

$$I_{driveline\_rear\_end} = 0.5 \times I_{trans} + \frac{I_{axle\_F} \times I_{axle\_R}}{I_{axle\_R} \times (1 - T_{bias\_to\_rear})^2 + I_{axle\_F} \times T_{bias\_to\_rear}{}^2} \tag{4}$$

The total driveline inertia, $I_{driveline}$, is derived by the following equation:

$$\frac{1}{I_{driveline}} = \frac{1}{I_{driveline\_front\_end}} + \frac{1}{I_{driveline\_rear\_end}} \tag{5}$$

The torsional stiffness ($K_{driveline}$) and damping coefficient ($D_{driveline}$) of the entire driveline is derived by the natural frequency ($\omega_{n\_driveline}$) and damping ratio ($\zeta_{driveline}$), such as:

$$\begin{aligned} K_{driveline} &= \omega_{n\_driveline}{}^2 \cdot I_{driveline} \\ D_{driveline} &= 2\zeta_{driveline} \cdot \omega_{n\_driveline} \cdot I_{driveline} \end{aligned} \tag{6}$$

In the above equations, the torsional stiffness and damping coefficient may change with the shift position (gear ratio of transmission). However, the user defined natural frequency and damping ratio is maintained during the simulation.

Multi-axle Powertrain

In TruckSim, the VS powertrain model supports up to a 10-wheel drive. Figure 19 shows the screen that assembles the information needed to define a 10-wheel drive powertrain. The multi-axle screen has the same items as the assembly screen for a 4-wheel drive system (Figure 15), but they differ in that the 10-wheel drive has more transfer cases/inter-axle differentials (8, 9) and differentials on drive axles (10 – 13).

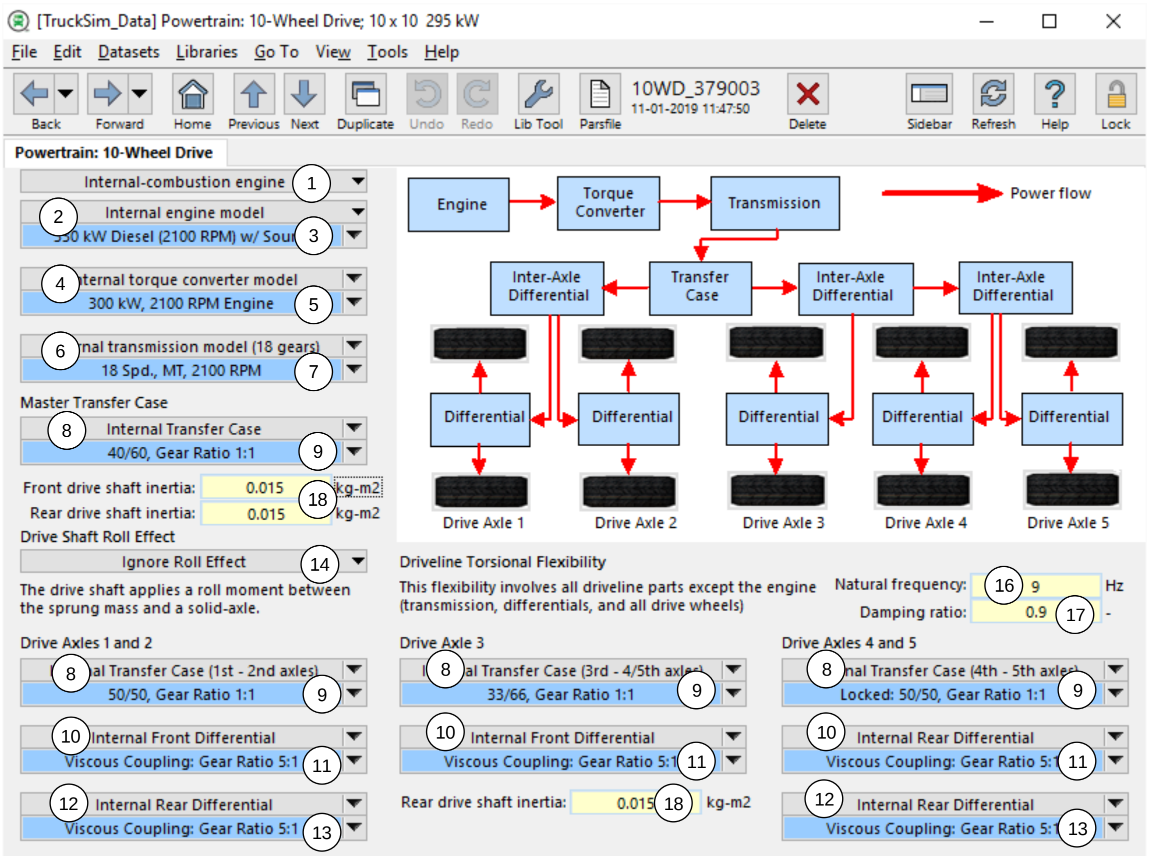

Figure 19. Powertrain assembly screen for a 10-wheel drive system.

18 Spin inertia of the drive shafts to the inter-axle differentials (keyword = `IDS(IDIFF)`).

> **Note:** The inter-axle differentials specified by **Powertrain: Transfer Case** screens do not include a shaft inertia field. Therefore, they are specified on the powertrain assemble screen. On the other hand, the spin inertia of the drive shaft to each of the drive axles is set on **Powertrain: Front Differential** or **Rear Differential** screen.

There are several powertrain systems available in TruckSim: 2-wheel, 4-wheel, 6-wheel, and 10-wheel drive, and those drive systems are applied to the back axles on the lead unit only (not the trailer). This is in the case that the number of suspension axles on the lead unit are five or less. For example, if the lead unit has four axles and the 4-wheel drive system is selected, the powered driven axles are the 3rd and 4th axles. In case that the lead unit has more than 5 axles, the drive systems are applied at the 5th axle only. The drive axles in the multi-axle vehicles are summarized in Table 1, where “D” denotes a drive axle, and “\” denotes it’s not applicable.

Table 1. Drive axles on multi-axle vehicles with various types of powertrain system.

Number of suspension axles	2-axle		3-axle			4-axle				5-axle					X-axle (5 <)						
Axle number	1	2	1	2	3	1	2	3	4	1	2	3	4	5	1	2	3	4	5	6	X
2WD (FWD)	D			D				D					D					D			
2WD (RWD)		D			D				D					D					D		
4WD	D	D		D	D			D	D				D	D				D	D		
6WD			D	D	D		D	D	D			D	D	D			D	D	D		
8WD						D	D	D	D		D	D	D	D		D	D	D	D		
10WD										D	D	D	D	D	D	D	D	D	D		

Internal-Combustion Engine

The engine is the power source of the vehicle when the driveline model is engaged. Engines are typically characterized by the flywheel torque measured on a dynamometer as a function of throttle position, *throttle*, and rotational speed, ω_e. These properties are defined in a table lookup of torque versus engine speed for different throttle settings, such as:

$$T_e = f_{et}(throttle, \omega_e) + T_{e\_control} \tag{7}$$

where $T_{e\_control}$ is an additional engine torque which is modulated by ESC/TCS controller, and its details are described in the following subsection (page 19).

> **Alert** The throttle variable in CarSim and TruckSim is used throughout the powertrain, for determining engine torque, gear shifting, the built-in speed controller, ESC, etc. The range of throttle is defined as zero to one. The VS Math Models check the value, setting the throttle to zero if it would otherwise be negative, and setting it to 1.0 if it would otherwise have a value greater than one. Be aware of this when creating tables for open-loop throttle or setting values with external software that will be imported into CarSim or TruckSim.

The relationship between the engine torque (T_e), engine's moment of inertia (I_e), engine angular acceleration (α_e), moment of inertia of torque transfer device engine side (I_{tc_in}), and torque transfer device input torque (T_{tcin}) are

$$(I_e + I_{tc\_in})\alpha_e = T_e - T_{tcin} \tag{8}$$

Engine angular speed is obtained in each time step by integrating the differential equation:

$$\dot{\omega}_e = \alpha_e = \frac{T_e - T_{tcin}}{I_e + I_{tc\_in}} \tag{9}$$

The engine rotation angle is given by

$$\dot{\phi}_e = \omega_e \tag{10}$$

The Engine Screen

The engine parameters and `MENGINE` Configurable Function involved in these engine calculations are set on the **Powertrain: Engine** screen (Figure 20) using the controls described below.

Figure 20. Screen for an engine.

1. Checkbox for using a 1st order time delay of the engine throttle. When checked, data fields (2 and 3) are shown that specify the time constants. If not checked, the engine throttle responds instantly without delay.

2. Dynamic time constant for opening the engine throttle (keyword = `TC_TH_APP`).

3. Dynamic time constant for closing the engine throttle (keyword = `TC_TH_REL`).

4. Optional link to a **Powertrain: Fuel Consumption Rate** dataset defining the rate of fuel consumption for this engine. When linked, the fuel consumption rate (kg/sec) and total fuel consumption (kg) for the run are calculated with the `FUEL_RATE` Configurable Function.

(5) Engine rotational inertia at crankshaft (keyword = IENG) . This parameter includes the inertia properties of all parts that spin with the engine output shaft and possibly portions of the hydraulic torque converter or clutch.

(6) Idle speed (keyword = AV_ENG_IDLE). This is the static engine rotational speed when there is zero throttle input. It provides a minimum initial engine speed when the vehicle is at rest.

(7) Speed where a clutch will disengage to avoid stalling (keyword = AV_ENG_LOW_CLUTCH) if the vehicle is at low speed and has a mechanical clutch (OPT_CLUTCH > 0) that is operated with a built-in closed-loop shift controller (OPT_CLUTCH_MODE = 1). If the powertrain has a torque converter (OPT_CLUTCH = 0) or the closed-loop shift controller is not used (OPT_CLUTCH_MODE = 0), then this parameter is ignored and will not be listed in the Echo file.

(8) Tabular data for engine torque (root keyword = MENGINE).

(9) Miscellaneous link for advanced users.

Turning the Engine Off and On

The parameter OPT_ENGINE_RUNNING turns the engine off (OPT_ENGINE_RUNNING = 0) or on (OPT_ENGINE_RUNNING = 1). The default value is 1. This parameter can be found in the Engine section of an Echo file (Figure 9, page 7).

The parameter OPT_ENGINE_RUNNING enables, for example, a start/stop controller to turn the engine off when the vehicle comes to a stop and to turn the engine on when the driver releases the brake pedal. The intended engine speed after startup, which can be set by the state variable SV_AV_ENG, must be high enough to prevent stalling the engine. In the start/stop example, the user may wish to set engine speed to the idle speed defined by the parameter AV_ENG_IDLE (also shown in the Echo file in Figure 9). This could be accomplished by typing SV_AV_ENG = AV_ENG_IDLE in a miscellaneous yellow field in an Event which turns the engine on.

Note: The state of OPT_ENGINE_RUNNING will not automatically change from 1 (running) to 0 (not running) if the engine is stalled by other means such as keeping the transmission clutch engaged when the vehicle reaches zero speed. Because OPT_ENGINE_RUNNING is a parameter rather than a variable, it needs to be explicitly set to 0 to turn the engine off, then back to 1 to turn the engine on.

ESC/TCS Torque Control Interface

ESC (Electric Stability Control) or TCS (Traction Control System) is required by regulations for all passenger cars since 2012. In these controllers, the engine torque is often modulated to minimize an excessive engine torque to prevent an instability due to wheel slipping. Further, some autonomous throttle control systems assist when climbing gravel hills.

With these controllers in mind, VS powertrain includes a controllable engine torque $T_{e\_control}$ in Equation 7.

The ESC/TCS controller typically commands a demand torque to the engine based on the driver requesting engine torque and some vehicle operating states, such as speed, yaw rate, wheel slip ratio, etc.

The VS model does not have a built-in ESC/TCS controller. A control algorithm defined with VS Commands or from an external model such as Simulink, actual hardware ECU, etc., provides the torque request $T_{e\_ESC\_rq}$, which is accessed in the VS Solver through the import variable `IMP_MENGINE_ESC_REQUEST`.

The engine torque requested by the driver model ($T_{e\_DRV\_rq}$) is exportable from the VS Solver to outside controller through an output variable (`M_Eng_Rq`) and is calculated based on the current engine speed with throttle level, such as:

$$T_{e\_DRV\_rq} = f_{et}(throttle, \omega_e) \tag{11}$$

The VS model has an internal P+I controller which modulates the engine torque, $T_{e\_control}$, in Equation 7 to meet the ESC's torque demand. The internal controller has three different operational states distinguished by an import variable (`IMP_ESC_ENGINE_CON_STATE`), 0: no control as default; 1: reduce; or 2: increase the engine torque to meet the torque request from ESC. For example, if the ESC is the reduce state (`IMP_ESC_ENGINE_CON_STATE = 1`), the ESC's target is the smaller of ESC and driver demand, such as:

$$\begin{aligned}
&if \ (ESC_state = 1) \\
&\quad T_{e_target} = \min\{T_{e_ESC_rq}, T_{e_DRV_rq}\} \\
&else \ if \ (ESC_state = 2) \\
&\quad T_{e_target} = \max\{T_{e_ESC_rq}, T_{e_DRV_rq}\} \\
&else \ if \ (ESC_state = 0) \\
&\quad T_{e_target} = T_e
\end{aligned} \tag{12}$$

The time derivative of the engine control torque is:

$$\dot{T}_{e\_control} = \left(T_{e\_target} - T_e\right) G_{P\_ESC} + \int \left(T_{e\_target} - T_e\right) dt \ G_{I\_ESC} \tag{13}$$

All import and export variables related with the ESC torque control are summarized in Table 2 and Table 3, respectively. PI parameters are summarized in Table 4.

Table 2. Import variables related with ESC/TCS torque control

Keyword	**Notation**	**Description**
`IMP_ESC_ENGINE_CON_STATE`	*ESC_state*	ESC engine torque control state
`IMP_MENGINE_ESC_REQUEST`	$T_{e\_ESC\_rq}$	Engine torque requested by ESC/TCS

Table 3. Export variables related with ESC/TCS torque control

Keyword	Notation	Description
`ESC_Stat`	*ESC_state*	ESC engine torque control state
`M_Eng_Rq`	$T_{e\_DRV\_rq}$	Driver requesting engine torque
`M_EngEsc`	T_{e_target}	ESC targeting engine torque
`RgearDLT`	---	Driveline total gear ratio

Table 4. PI parameters for ESC/TCS torque control

Keyword	Notation	Units	Description
`ENGINE_ESC_PG`	G_{P_ESC}	1/s	P gain of engine control
`ENGINE_ESC_IG`	G_{I_ESC}	1/s2	I gain of engine control

Note Some ESC/TCS control systems use driver or ESC torque request signal at the wheels instead of the engine. In such cases, users can use an export variable `RgearDLT`, which is the total gear ratio from the engine to the wheels through transmission, transfer case (if any) and differentials.

Torque Transfer to Transmission

Torque is transmitted from the engine to the transmission by either a hydraulic torque converter or a mechanical clutch. The type of torque transfer is specified with the parameter `OPT_CLUTCH`. This parameter is set automatically based on the type of library selected from the Powertrain top-level screen ring control (4, Figure 15 and Figure 21).

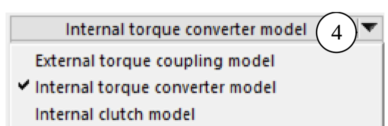

Figure 21. Options for torque converters with internal-combustion engine.

Hydraulic Torque Converter

If the internal torque converter is selected (`OPT_CLUTCH` retains the default value of 0), the torque at the output side of a torque converter (T_{tcout}) is given by the characteristic table (f_{tr}), which is the torque ratio (T_{tcout} / T_{tcin}) as a function of speed ratio (S_{tc}), multiplying the torque at the input side.

$$T_{tcout} = f_{tr}(S_{tc}) \times T_{tcin} \tag{14}$$

Torque at the input side of the torque converter (T_{tcin}) is equal to the torque load on the engine given by the characteristic table (f_{tki}), which is the inverse torque capacity (1/K) as a function of the speed ratio, ($S_{tc} = \omega_{tco} / \omega_e$), multiplying angular speed of engine.

$$T_{tcin} = sign\{f_{tki}(S_{tc})\} \times \{f_{tki}(S_{tc}) \times \omega_e\}^2 \tag{15}$$

In general, the torque converter is characterized by the torque capacity (K). However, to account for engine braking, it is difficult to describe the model directly in terms of K because normally $K \to \infty$ as $\omega_{tco}/\omega_e \to 1$. Therefore, the capacity is described by a table for $1/K$ as a function of ω_{tco}/ω_e. When $\omega_{tco}/\omega_e > 1$, the sign of K is assumed to be negative, thus exerting a retarding torque on the transmission, and ultimately, the wheels.

If a lockup torque converter is employed (`OPT_CLUTCH` = 2), a mechanical clutch is applied parallel to this hydraulic equation. This is explained in the next sub-section. The lockup schedule is described in the section, **Transmission**.

The above parameters and table function involved in these hydraulic torque converter calculations are set on the screen in Figure 22, using the screen items described below.

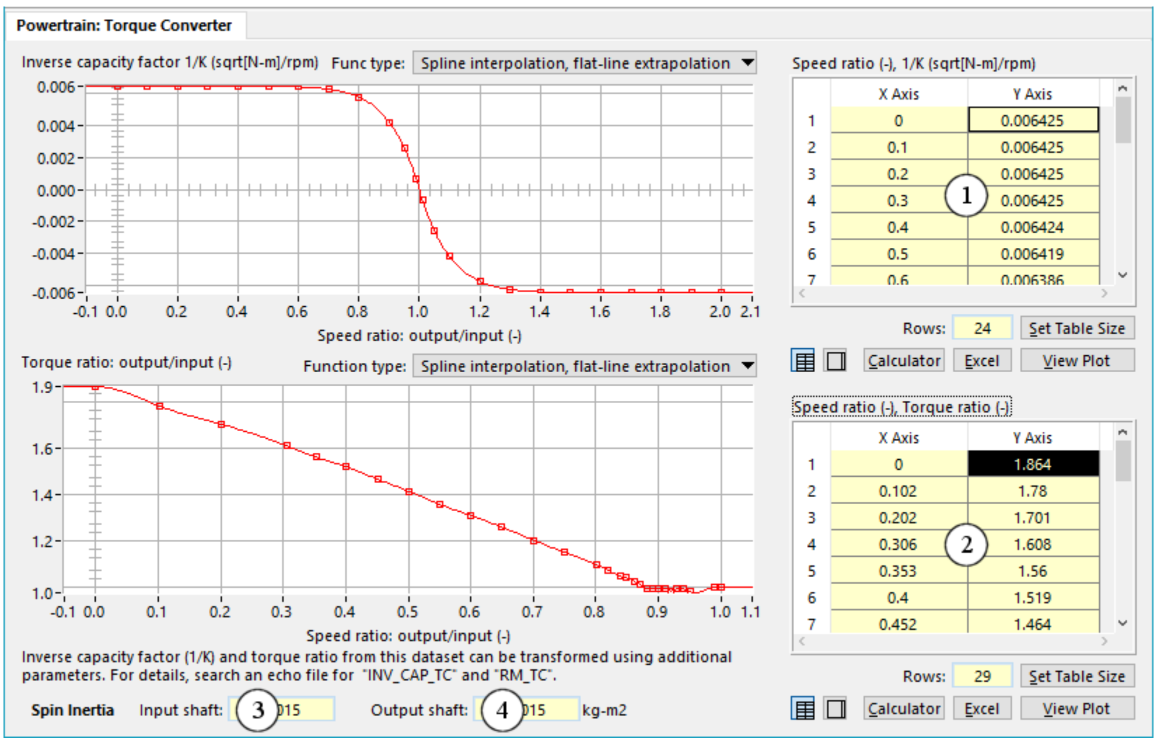

Figure 22. Screen for a torque converter.

① Inverse of the torque converter capacity as a function of speed ratio (root keyword = `INV_CAP_TC`).

② Torque amplification as a function of speed ratio (root keyword = `RM_TC`).

③ Spin inertia of the input shaft of the torque converter (keyword = `ITC_INPUT_SHAFT`).

④ Spin inertia of the output shaft of the torque converter (keyword = `ITC_OUTPUT_SHAFT`).

Mechanical Clutch

If the internal clutch model is selected the Powertrain top-level screen ring control (4, Figure 15 and Figure 21, page 21), a link is made to the **Powertrain: Clutch Torque** library (Figure 24, page 25). The linked dataset sets the parameter `OPT_CLUTCH` to 1, enabling the built-in clutch model.

Slipping and Locked states

The clutch has two states: slipping or locked. Between those two states, the equations to calculate the torque and degree-of-freedom are different. Firstly, those states are distinguished by the following operating conditions.

$$\begin{array}{l}
\text{if currently slipping then} \\
\quad \text{If } \mathrm{abs}(T_{clutch_cap}) > \mathrm{abs}(T_{clutch_lock}) \quad AND \quad (d\omega_{clutch} \times d\omega_{clutch_old}) < 0.0 \\
\quad \text{then} \quad \text{'chage to locked'} \quad \text{else} \quad \text{'keep slipping'} \\
\text{else (currently locked)} \\
\quad \text{If } \mathrm{abs}(T_{clutch_cap} \times 1.02) > \mathrm{abs}(T_{clutch_lock}) \\
\quad \text{then} \quad \text{'keep locked'} \quad \text{else} \quad \text{'change to slipping'}
\end{array} \tag{16}$$

Where $d\omega_{clutch}$ is the speed differential between input and output plates of the clutch (ω_e-ω_{tco}) and $d\omega_{clutch\_old}$ is $d\omega_{clutch}$ from one calculation step ago. The term of the condition "($d\omega_{clutch\_old}$ x $d\omega_{clutch}$) < 0.0" represents that the speed differential of the clutch reverses to the other direction. T_{clutch_cap} denotes the torque capacity of clutch, which is defined by the table function as:

$$T_{clutch\_cap} = f_{clutch\_cap}(Clutch\_displacement) \tag{17}$$

Clutch_displacement is the input value (0 – 1) from the control from the driver. T_{clutch_lock} denotes the theoretically calculated torque load on the locked clutch, whose value is calculated by:

$$T_{clutch\_lock} = \frac{T_e - \dfrac{T_g}{N_{trans}} \cdot \dfrac{I_e + I_{tc\_in}}{0.5 I_{trans} / N_{trans}{}^2}}{1 + \dfrac{I_e + I_{tc\_in}}{0.5 I_{trans} / N_{trans}{}^2}} \tag{18}$$

Note The derivation of the torque load on the locked clutch is described in the Appendix (page 56).

The reason why the clutch torque capacity is multiplied by 1.02 in the currently locked condition of equation 16 is that the static friction is considered 2% greater than the dynamic friction.

Overall, when the clutch is slipping, if the torque capacity (T_{clutch_cap}) is bigger than the torque load (T_{clutch_lock}) and the speed differential between the input/output clutch plates is reversed to the other direction then the clutch is locked. While the clutch is locked, if the torque load (T_{clutch_lock}) exceeds more than 2% of the torque capacity (T_{clutch_cap}), the clutch starts to slip.

When the clutch is slipping

If the clutch is slipping, the torque reacting to the engine (T_{tcin}) and the torque to the transmission input shaft (T_{tcout}) are the same, such as:

$$T_{tcin} = T_{tcout} = \mathrm{sign}\left(T_{clutch\_cap}, d\omega_{clutch}\right) \tag{19}$$

where `sign` is the sign function that the sign of the first term (T_{clutch_cap}) depends on the second term ($d\omega_{clutch}$). When $d\omega_{clutch}$ is positive, T_{tcin} is also positive in this case.

When the clutch is locked

If the clutch is locked, the clutch torque is treated as same as engine torque, the degree-of-freedom of the engine crankshaft is removed, and both sides of the clutch are treated as "one unit". Therefore, Equation 9 and 10 are ignored and angular acceleration and angular speed of engine are treated as:

$$\begin{aligned} &T_{tcin} = T_{tcout} = T_e, \\ &\dot{\omega}_e = \alpha_e = \dot{\omega}_{tco}, \\ &\omega_e = \omega_{tco}. \end{aligned} \tag{20}$$

However, the clutch torque for plot is compensated by the engine inertial term only when the clutch is locked such as:

$$T_{tcin}{}^{*} = T_{tcout}{}^{*} = T_e - (I_e + I_{tc\_in})\alpha_e. \tag{21}$$

> **Note** $T_{tcout}{}^{*}$ is also used for the criteria of driving or coasting efficiencies of the transmission, transfer cases and differentials.

Clutch torque screen

Figure 24 shows the **Powertrain: Clutch Torque** screen with the following controls.

1. Checkbox for using a 1st order time delay of the clutch torque capacity (keyword = `OPT_CLUTCH_DELAY`). When checked (Figure 23), extra data fields (2 and 3) are shown that specify the time constants. If not checked, the clutch torque responds instantly without delay.

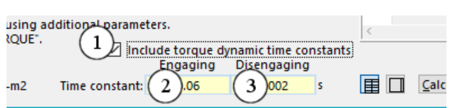

Figure 23. Display when option for dynamic time constant is enabled.

2. Dynamic time constant for engaging the clutch (keyword = `TC_CLUTCH_ENGAGE`).
3. Dynamic time constant for disengaging the clutch (keyword = `TC_CLUTCH_DISENGAGE`).
4. Spin inertia of the input shaft of the clutch (keyword = `ITC_INPUT_SHAFT`).

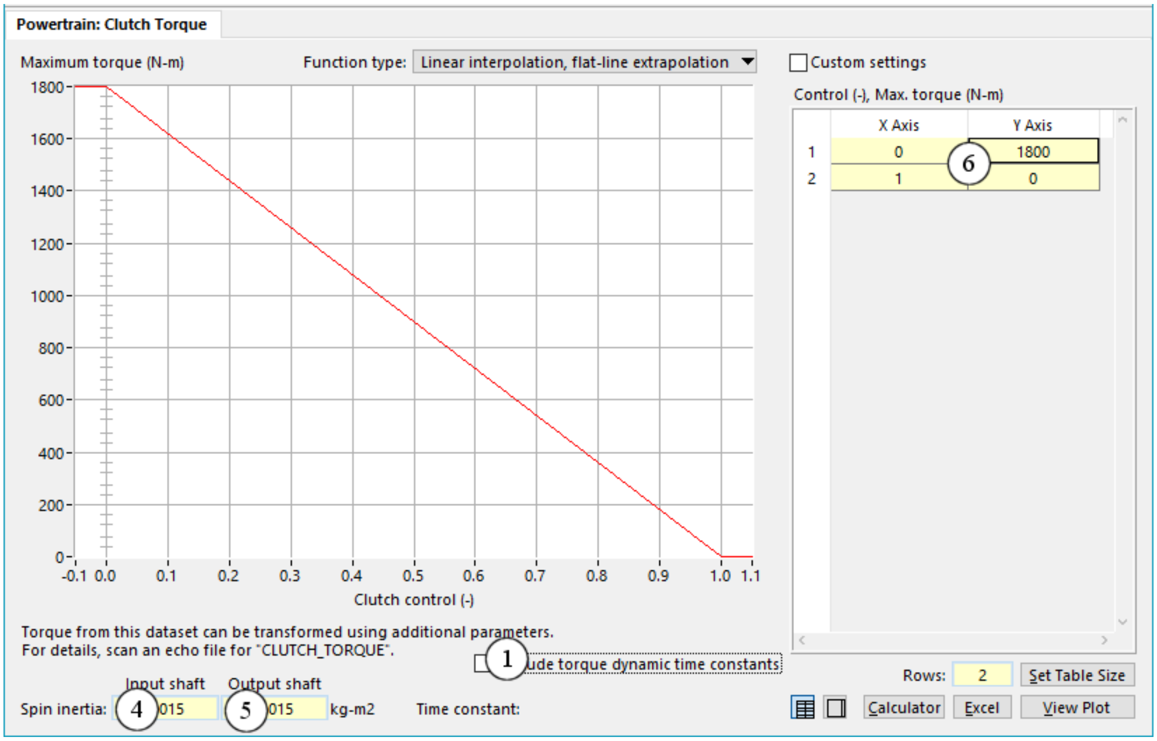

Figure 24. Screen for a mechanical clutch.

(5) Spin inertia of the output shaft of the clutch (keyword = `ITC_OUTPUT_SHAFT`).

(6) Tabular data for the maximum torque available from a mechanical clutch as a function of a control (root keyword = `CLUTCH_TORQUE`). When the control is 1 (or greater), the clutch disengages such that no torque is transferred between the two shafts.

Transmission

Figure 25 shows the two states of the transmission: the top diagram is geared position (either reverse, 1st gear or higher gear shift position), and the bottom diagram is the neutral position. When the transmission is geared, it has one degree-of-freedom, which is the transmission's torsional twist. On the other hand, when the transmission is in neutral, it has an additional degree-of-freedom, which is the spin of the torque transfer device's output shaft.

The transmission output shaft torque (T_g) is given by the torsional spring-damper, such as:

$$T_g = K_{driveline} \times (\phi_{grout} - \phi_g) + D_{driveline} \times (\omega_{grout} - \omega_g) \, , \tag{22}$$

where the torsional stiffness ($K_{driveline}$) and damping coefficient ($D_{driveline}$) of the entire driveline are given in Equation 6.

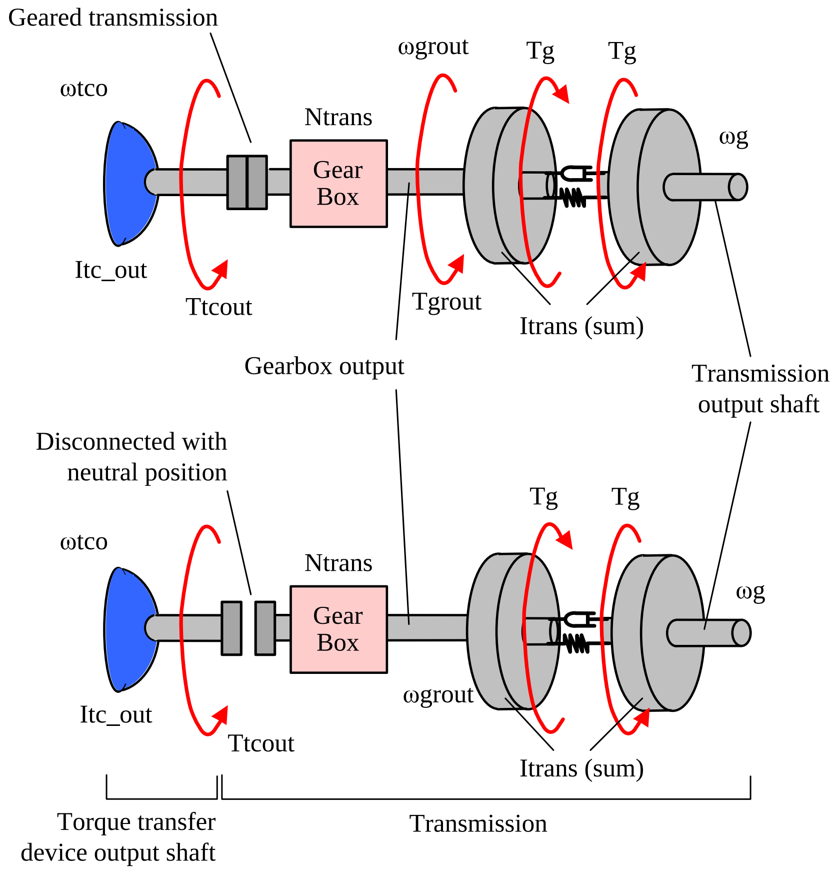

Figure 25. Diagrammatic figures of the VehicleSim transmission model: geared transmission (above diagram) and disconnected with neutral position (bottom diagram).

The other equations for the spin and torque regarding the transmission vary with whether geared or neutral, or whether the main clutch is engaged or disengaged (total 4 cases) as described below.

When the Transmission is in Gear

When the transmission is geared, the transmission gear ratio (N_{trans}) is associated with either the selected gear number or continuously variable. The output torque of the transmission gearbox (T_{grout}) is given by the torque transfer device output torque (T_{tcout}), gear ratio and efficiency depending on whether the engine drives the wheel, or the wheels drive the engine, such as:

$$\begin{aligned} T_{grout} &= N_{trans} \times T_{tcout} \times E_{trans} \quad (T_{tcout}{}^{*} \geq 0) \quad or \\ T_{grout} &= N_{trans} \times T_{tcout} / E_{trans\_rev} \quad (T_{tcout}{}^{*} < 0) \end{aligned} \tag{23}$$

where E_{trans} is the efficiency (multiplying) when the engine drives the wheels. On the other hand, E_{trans_rev} is the efficiency (dividing) when the wheels drive the engine. Those two efficiencies are switched depending on the direction of the torque through the transmission.

Note All of the efficiency parameters used in the following descriptions have two cases, switched by the direction of T_{tcout}^{*}, which is compensated by engine inertial term when the clutch is locked in Equation 21.

The gearbox output speed is given by:

$$\begin{aligned}&\text{If clutch is slipping}\\&\dot{\omega}_{grout} = \alpha_{grout} = \frac{T_{grout} - T_g}{I_{tc\_out} \cdot N_{trans}{}^2 + 0.5 I_{trans}}\\&\text{else (clutch is locked)}\\&\dot{\omega}_{grout} = \alpha_{grout} = \frac{T_{grout} - T_g}{(I_e + I_{tc\_in} + I_{tc\_out}) \cdot N_{trans}{}^2 + 0.5 I_{trans}}\end{aligned} \tag{24}$$

where in case of the locked clutch, the engine, torque transfer device output shaft and gearbox are all treated as one unit ($T_{tcout} = T_e$).

The angular speed of the torque transfer device output, ω_{tco}, is calculated by the transmission output angular speed, ω_{grout}, multiplied by the transmission gear ratio, such as:

$$\omega_{tco} = N_{trans} \times \omega_{grout} \tag{25}$$

The rotation angle of the torque transfer device output, ϕ_{tco}, is calculated by the transmission output rotation angle, ϕ_{grout}, multiplied by the transmission gear ratio, such as:

$$\phi_{tco} = N_{trans} \times \phi_{grout} \tag{26}$$

When the Transmission is in Neutral

If the transmission is in neutral position (see the bottom diagram of Figure 25), the gearbox output speed is:

$$\dot{\omega}_{grout} = \alpha_{grout} = \frac{-T_g}{0.5 I_{trans}} \tag{27}$$

Furthermore, the output shaft of the torque transfer device has an independent degree-of-freedom. Its speed is given by:

$$\begin{aligned}&\text{If clutch is slipping}\\&\dot{\omega}_{tco} = \alpha_{tco} = \frac{T_{tcout}}{I_{tc\_out}}\\&\text{else (clutch is locked)}\\&\dot{\omega}_{tco} = \alpha_{tco} = \frac{T_e}{I_e + I_{tc\_in} + I_{tc\_out}}\end{aligned} \tag{28}$$

For any case (whether transmission is geared or neutral), the gearbox output rotation angle is given by:

$$\dot{\phi}_{grout} = \omega_{grout} \tag{29}$$

Transmission Screen

When the powertrain screen is set to an internal combustion engine, the transmission option is available for internal or external transmission models. The internal model option links to the **Powertrain: Transmission (18 Gears or CVT)** library (Figure 26).

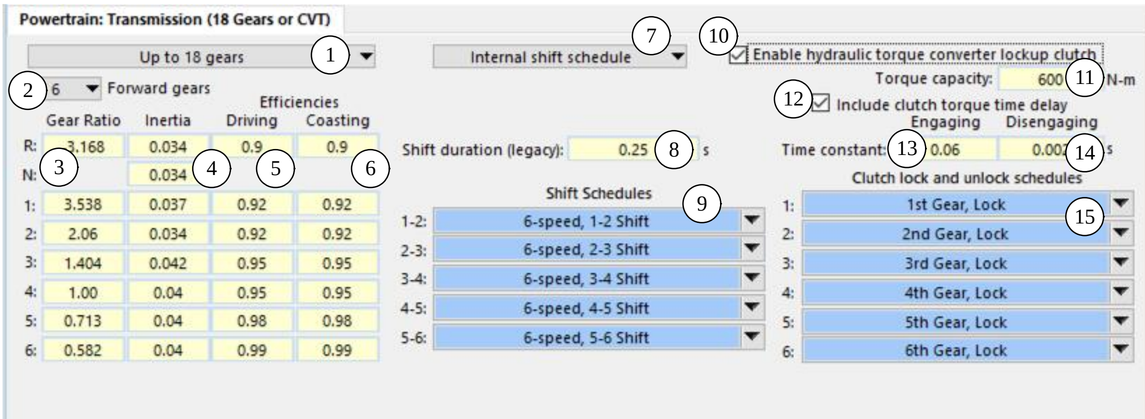

Figure 26. Screen for a transmission.

Use this screen to specify the properties of an automatic/manual transmission with up to 18 gears or continuously variable transmission (CVT), using the controls described below.

1 Drop-down list for specifying the type of the transmission gears (keyword = `OPT_TR_GEAR_INTERNAL`). The option chosen determines the kind of the transmission that appears directly underneath (Figure 27).

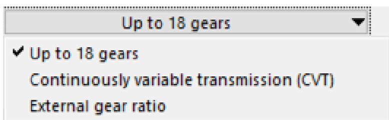

Figure 27. Drop-down list for types of transmission gearing.

1. Up to 18 gears: specify the gear ratio, inertia, and efficiencies for each gear (3 - 6, Figure 26).

2. Continuously variable transmission (CVT): specify the gear ratio, inertia, and efficiencies by using tables, as described in a following subsection. When this option is selected, all the gear-specific controls on the screen are hidden except for reverse and neutral. More information about this option is presented in a later subsection (page 33).

3. External gear ratio: specify the gear ratio, inertia, and efficiencies via import variables from external software. When this option is selected, nearly all the other controls on this screen are hidden.

(2) Drop-down list to define the number of gears in the transmission (keyword = `NGEARS`). Any parameters involving gears above this number are ignored by the math model, and any controls on this screen are hidden.

(3) Driveline gear ratios (keywords = `R_GEAR_TR_REVERSE` and `R_GEAR_TR(IGEAR)`). The forward gear ratios must be positive, and the reverse gear ratio must be negative.

(4) Driveline inertias (keywords = `ITR_REVERSE`, `ITR_NEUTRAL`, and `ITR(IGEAR)`). All values should be positive. For front and rear-wheel drive, the equivalent inertias are the inertial loads placed on the respective differential. For both part-time and full-time four-wheel drive, the equivalent inertias are the inertial loads placed on the transfer case, and the drive shafts are assumed to have zero inertia.

(5) Driving efficiencies for each gear (keywords = `R_EFF_TR_F_REVERSE` and `R_EFF_TR_F(IGEAR)`). When power is being transferred from the transmission input shaft to the output shaft (in normal operation when the engine is providing power to the wheels), the torque of the input shaft is multiplied by this coefficient (Equation 23). It accounts for friction and other losses.

(6) Coasting efficiencies for each gear (keywords = `R_EFF_TR_R_REVERSE` and `R_EFF_TR_R(IGEAR)`). When power is being transferred from the transmission output shaft to the input shaft (when the engine is providing a braking effect), the torque of the input shaft is divided by this coefficient (Equation 23). It accounts for friction and other losses.

(7) Drop-down list for selecting an external or internal shift schedule (keyword = `OPT_SHIFT_INTERNAL`). The data link for the shift schedule for each gear (9) is hidden when the external shift schedule is selected.

(8) Shift duration (legacy) is the transition time to change from one gear to another for automatic transmission with a hydraulic torque converter (keyword = `T_SHIFT`) in case the parameters for a specific gear (`T_SHIFT_UP` and `T_SHIFT_DOWN`) were not set and retain the default value of –1.

> **Note** Shift duration time can be set separately for each gear on **Powertrain: Shift Schedule** screen (keywords: `T_SHIFT_UP` and `T_SHIFT_DOWN`). This is applicable only to automatic transmissions with a hydraulic torque converter. Shift duration for a manual transmission (or automated system with clutch control) is accessed on the **Control: Clutch Shifting Timelines (Closed Loop)** screen as described in the Help document *Driver Controls*.

(9) Links to **Powertrain: Shift Schedule** data sets. Each linked data set provides criteria for upshifting and downshift between the gears associated with the link (Table 5).

Table 5. Summary of gear shift and lock-up clutch control keywords (for up to 18 gears).

Library Name	**Root Keyword**	**Description**	**Index**

Powertrain: Shift Schedule	`UPSHIFT_TRANS`
	`DOWNSHIFT_TRANS`
	`T_SHIFT_UP`
	`T_SHIFT_DOWN`
		Gear upshift and downshift schedule using throttle position and transmission output speed.	`IGEAR`

Powertrain: AT Clutch Schedule	`LOCK_AT` and `UNLOCK_AT`	Torque converter lockup and unlock schedule using throttle position and transmission output speed.	
Not applicable	`LIMIT_UPSHIFT` and `LIMIT_DOWNSHIFT`	Limits to how much change is allowed for a gear shift.	

> **Note** Two of the parameters in Table 5 are not set automatically by any of the VS Browser screens: `LIMIT_DOWNSHIFT` and `LIMIT_UPSHIFT`. When left at the default values of 1, the internal shifting uses a single set of upshift and downshift Configurable Function datasets to consider shifting one gear up or down. When set to a higher number (e.g., `LIMIT_UPSHIFT` = 3), the controller will check the appropriate shift Configurable Function dataset for the largest shift possible, subject to the limit that the highest gear allowed is `NGEARS` and the lowest gear is 1. If the combination of throttle and transmission speed would indicate a shift (e.g., upshift from gear 3 to 7 if `LIMIT_UPSHIFT` = 3), then a shift is made. If not, the controller attempts the next closer gear (e.g., upshift from 3 to 6). If not successful, it goes to the next closer gear (e.g., from 3 to 5) and so on until all shifts from the limits down to 1 have been tested.

(10) Checkbox to include a lockup clutch in the torque converter of an automatic transmission. Checking the box reveals a links for each gear to define locking and unlocking control conditions for the lockup clutch. This box must be unchecked when a manual clutch is linked on the main **Powertrain** screen.

(11) Maximum torque capacity of the lockup clutch (keywords = `M_LOCKUP_CLUTCH_CAP`).

(12) Checkbox for using a 1st order time delay of the clutch torque capacity (keyword = `OPT_CLUTCH_DELAY`). When checked, extra data fields ((13) and (14)) are shown that specify the time constants. If not checked, the clutch torque responds instantly without delay.

(13) Dynamic time constant for engaging the clutch (keyword = `TC_CLUTCH_ENGAGE`).

(14) Dynamic time constant for disengaging the clutch (keyword = `TC_CLUTCH_DISENGAGE`).

(15) Links to **Powertrain: AT Clutch Schedule** data sets. These links are only visible if the above box (10) is checked. Each linked data set provides criteria for engaging and disengaging a torque converter lock-up clutch for the gear associated with the link (Table 5).

Shift Control

The gear of the transmission is determined in part by the transmission's mode of operation, specified by the value of the Configurable Function `MODE_TRANS`. This driver control setting can be set in the VS Browser by linking to a dataset from one of two libraries:

1. **Control Shifting (Open Loop).** Datasets in this library assign `MODE_TRANS` = 1 and set up a Configurable Function `GEAR_TRANS` that sets the gear to a constant or 1D function of time.
2. **Control: Shifting (Closed Loop)**. Datasets in this library set up the mode for shifting as described below.

When `MODE_TRANS` is -1, the reverse gear of the transmission is invoked. When `MODE_TRANS` is 0, the transmission is in neutral, and the output torque is zero. A mode of 1 means that the transmission gear is determined as an open-loop function of time as specified on the screen **Control: Shifting (Open Loop)**. Modes 2 through 18 define the highest gear that can be set when changing gear automatically according to the upshift and downshift schedule tables linked to the transmission screen. For example, if the mode is 3, then gears higher than 3 are never accessed.

The options for setting up the shifting behavior are described in the **Help** document **Controls > Driver Controls**, which also describes the open-loop shifting screen.

The internal shifting controller of the powertrain may be used to represent driver behavior with manual shifting, or automatic shifting from a hydraulic automatic transmission.

The controller shifts up or down by using the current throttle position (ranging between 0 and 1) and comparing the transmission output speed with values obtained from upshift and downshift Configurable Functions.

Upshifting occurs when the combination of transmission speed and throttle crosses an upshift line defined with the `UPSHIFT_TRANS` Configurable Function that is set in the **Powertrain Shift Schedule** library (①, Figure 28) along with a corresponding `DOWNSHIFT_TRANS` Configurable Function for downshifting ②.

The datasets for upshift and downshift limits are linked on the **Transmission** screen ⑨ (Figure 26, page 28).

Note that the Shift Schedule screen also has shift duration times for upshift ③ and downshift ④ that can be set to customize the shift times for each gear. If not specified here, the generic shift duration from the **Transmission** screen is used (⑧, Figure 26).

Figure 29 shows an example upshift diagram with an upshift boundary from 3rd to 4th gear. In this figure, the current throttle position is 0.6 (60%) and transmission output speed is 2000 rpm with the current gear position of 3rd gear. The upshift will happen if the throttle position is reduced below 0.38 keeping the same transmission speed, or if the transmission speed increases to more than 2600 rpm while keeping the same throttle position, or if a new combination of throttle and speed crosses the upshift line.

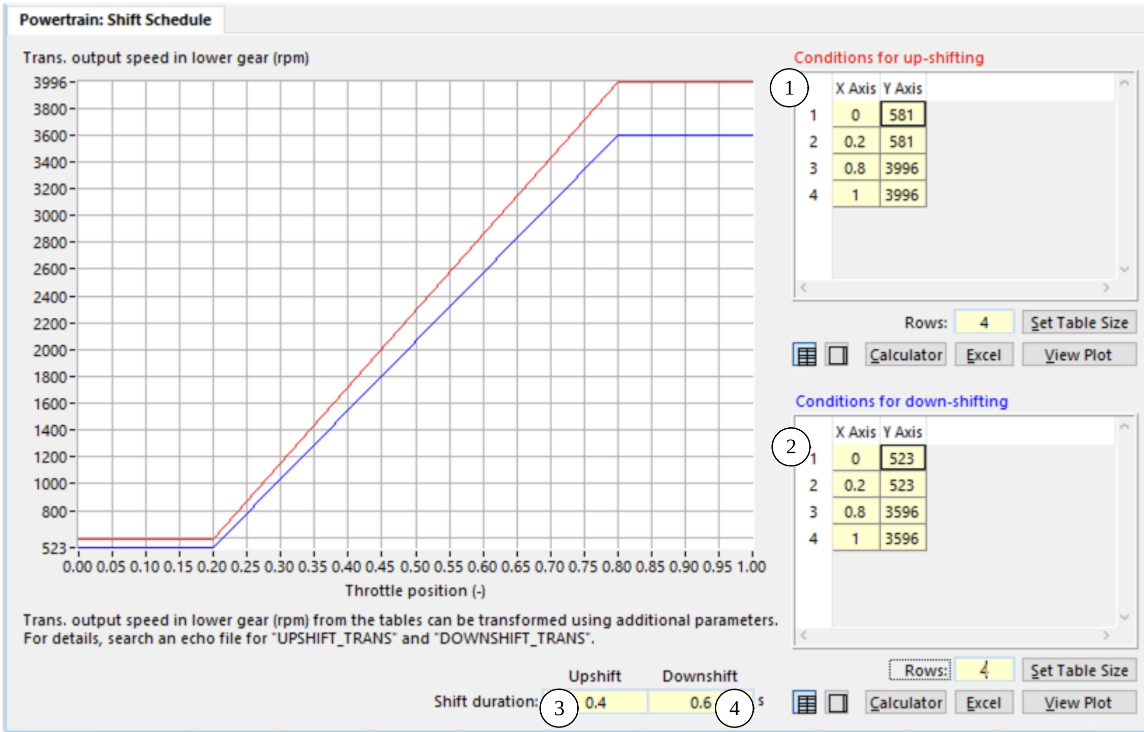

Figure 28. Shift schedule screen.

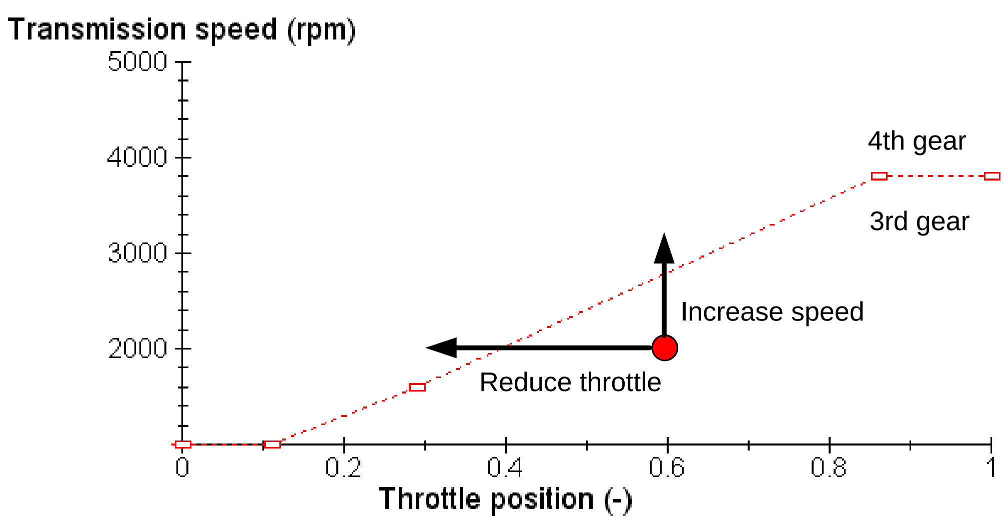

Figure 29. Example upshift diagram.

Downshifting occurs when the transmission speed decreases below a specified level, or the throttle position rises above a specified level. Figure 30 shows an example downshift diagram with a downshift boundary from 4^{th} to 3^{rd} gear. In this figure, the current throttle position is 0.6 (60%) and transmission output speed is 2000 rpm. A downshift will happen if the throttle position is increased above 0.82 keeping the same transmission speed, or if the transmission speed drops to less than 1200 rpm keeping the same throttle position.

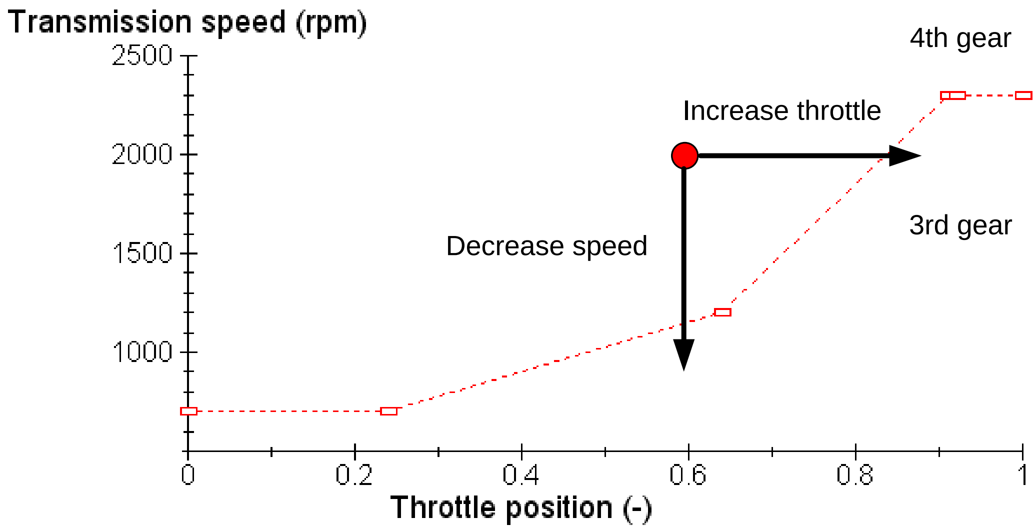

Figure 30. Example downshift diagram.

Continuously Variable Transmission (CVT)

When the transmission is continuously variable (CVT), most equations are as same as the equations (23 - 26) described in the earlier subsections for in Gear and in Neutral (pages 26 and 27), except that the transmission gear ratio (N_{trans}) is continuously variable as a function of the throttle position and the transmission output speed, such as:

$$N_{trans\_inst} = f_{cvt\_gear}(throttle,\ \omega_{tco}) \tag{30}$$

where N_{trans_inst} is the instant gear ratio which does not involve any time delay. The actual gear ratio applied to the transmission is expressed by a 1st order dynamic time delay such as:

$$\dot{N}_{trans} = \frac{N_{trans\_inst} - N_{trans}}{T_{c\_cvt}} \tag{31}$$

where T_{c_cvt} is the dynamic time constant, and N_{trans} is integrated and updated for every numerical calculation time step. In turn, the transmission efficiencies (E_{trans} and E_{trans_rev}) and transmission inertia (I_{trans}) are also continuously variable as the functions of the current transmission gear ratio, such as:

$$\begin{aligned} &E_{trans} = f_{cvt\_efficiency}(N_{trans}), \\ &E_{trans\_rev} = f_{cvt\_efficiency\_rev}(N_{trans}),\ and \\ &I_{trans} = I_{cvt\_input\_pulley} \times N_{trans}{}^{2} + I_{cvt\_output\_pulley}, \end{aligned} \tag{32}$$

where $I_{cvt\_input\_pulley}$ and $I_{cvt\_output\_pulley}$ are the inertial of the input and output pulley of the CVT, respectively.

Because the gear ratio is differentiable with time, the angular acceleration of the transmission input can be:

$$\dot{\omega}_{tco} = N_{trans}\ \dot{\omega}_{grout} + \dot{N}_{trans}\ \omega_{grout} \tag{33}$$

which yields the gearbox output speed given by:

If clutch is slipping

$$\dot{\omega}_{grout} = \alpha_{grout} = \frac{T_{grout} - T_g - (I_{tc\_out} + I_{cvt\_input\_pulley}) \cdot N_{trans} \cdot \dot{N}_{trans} \cdot \omega_{grout}}{I_{tc\_out} \cdot N_{trans}^{\ 2} + 0.5 I_{trans}}$$

else (clutch is locked)

$$\dot{\omega}_{grout} = \alpha_{grout} = \frac{T_{grout} - T_g - (I_e + I_{tc\_in} + I_{tc\_out} + I_{cvt\_input\_pulley}) \cdot N_{trans} \cdot \dot{N}_{trans} \cdot \omega_{grout}}{(I_e + I_{tc\_in} + I_{tc\_out}) \cdot N_{trans}^{\ 2} + 0.5 I_{trans}} \tag{34}$$

Equation 34 is like equation 24 but involves an additional term with the time derivative of transmission gear ratio. If the transmission gear ratio continuously varies (time differentiable) such as CVT, the gearbox output speed is calculated by equation 34 instead of equation 24.

On the **Powertrain: Transmission (18 Gears or CVT)** screen (Figure 31), select the menu item, **Continuously variable transmission (CVT)** from the drop-down list (1). With this setting, the screen is changed to remove settings for forward gears, as shown in the figure.

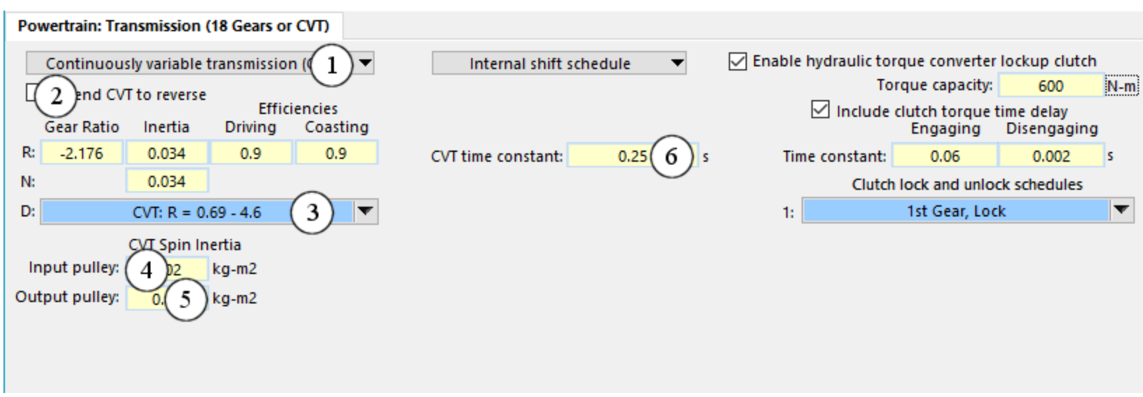

Figure 31. Alternate appearance of the transmission (Extended) screen for CVT settings.

> **Note** This section describes only the controls for the CVT on the **Powertrain: Transmission (18 Gears or CVT)** screen. The other controls are described in the previous subsection.

(1) Drop-down list for specifying the type of the transmission gears (keyword = `OPT_TR_GEAR_INTERNAL`). The option chosen determines the kind of the transmission that appears directly underneath:

1. Up to 18 gears: specifying the gear ratio, inertia, and efficiencies for each gear number,
2. Continuously variable transmission (CVT): specifying the gear ratio, inertia, and efficiencies by using tables (this item is selected in Figure 31), and

3. External gear ratio: specifying the gear ratio, inertia, and efficiencies via external importing variables.

② Checkbox to extend CVT settings for the reverse gear (keyword = `OPT_CVT_REVERSE`). If this box is checked, the constant values for the gear ratio, inertia and efficiencies for the reverse gear are hidden to show another blue link ③ to the **Powertrain: CVT Gear Ratio** library (Figure 32).

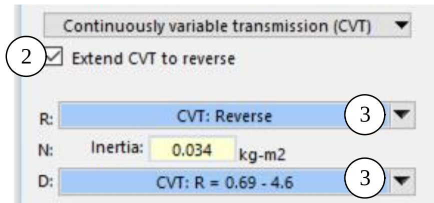

Figure 32. Extending the CVT to reverse.

③ Link(s) to **Powertrain: CVT Gear Ratio** data set, which in turn links to **Powertrain: CVT Efficiencies** data set (see Table 6).

Table 6. Summary of the continuously variable gear ratio and efficiencies control keywords.

Library Screen Name	**Root Keyword**	**Index**	**Description**
Powertrain: CVT Gear Ratio	`R_GEAR_CVT`	`ICVT`	CVT gear ratio as a function of throttle position and transmission output speed. The index refers either the drive (forward) or reverse.
Powertrain: CVT Efficiencies	`R_EFF_CVT_F` and `R_EFF_CVT_R`	`ICVT`	CVT driving and coasting efficiencies, respectively, as functions of the transmission gear ratio. The index refers either the drive (forward) or reverse.

④ Input pulley inertia (keywords = `ICVT_INPUT_PULLEY`).

⑤ Output pulley inertia (keywords = `ICVT_OUTPUT_PULLEY`).

⑥ Dynamic time constant for the CVT (keyword = `TC_RGEAR_CVT`).

Differential Systems

One or more differential systems transfer torque from the transmission to the individual drive wheels.

Overview of Variable Types of Differentials

The VS Math Models support multiple types of differential systems, which can be individually set in the front, rear, and center differentials. Table 7 summarizes the differential system types.

Table 7. Available differential systems.

System name	Location	Corresponding GUI screen
Viscous Coupling	Front	Powertrain: Front Differential
	Rear	Powertrain: Rear Differential
	Center	Powertrain: Transfer Case
Differential Clutch or LSD	Front Rear	Powertrain: Limited Slip Differential (Front or Rear), linked from each Differential screen.
	Center	Powertrain: Limited Slip Differential for Center Case, linked from Transfer Case screen.
Yaw Control Differential	Front Rear Center	Powertrain: Yaw Control Differential, linked from each Differential or Transfer Case screen.
Twin-Clutch	Front	Powertrain: Front Twin-Clutch Differential, linked from Front-Wheel Drive screen.
	Rear	Powertrain: Rear Twin-Clutch Differential, linked from Rear-Wheel Drive screen.

Viscous Coupling

Generally, the viscous coupling means a *speed-sensitive* limited slip differential using some hydraulic mechanism as a part of the differential system. The system can limit the slipping of one wheel or slipping of one end of the drive shaft (4WD). The viscous coupling is defined by a torque differential as a non-linear function of a speed differential using a table. The viscous coupling is available over the front, rear, and center differentials.

Differential Clutch

The mechanical friction mechanism applies to the front, rear and center differentials as shown in Figure 33. The clutch transmits a torque from the slipping side to the other side – therefore it can limit the slipping of one wheel or slipping of one end of the drive shaft (4WD). The clutch is defined by a maximum available torque as a non-linear function of a clutch control position, which is controlled by a simple control law or external signal through VS Commands, Simulink, or external code. The simple control law adopts a non-linear function of the sum of the output torques. Therefore, the system can behave as a *torque-sensitive* slip-limiting device. It is very similar to the limited slip differential (LSD).

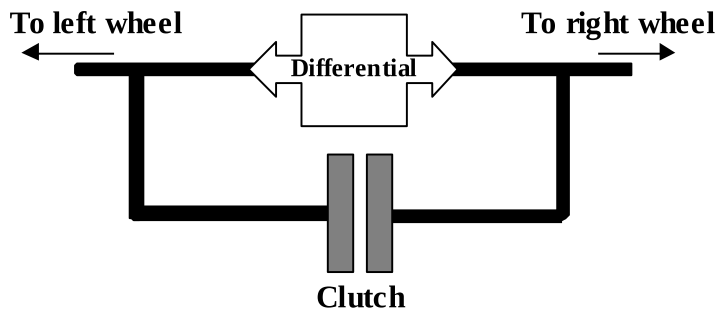

Figure 33: The clutch over the differential (Front or Rear).

Limited Slip Differential (LSD)

Limited Slip Differential (LSD) involves a mechanical friction clutch, which is very similar to the Differential Clutch. Generally, the clutch is pre-loaded by a spring to provide an initial torque that maintains minimum traction when a wheel slips. The loading of the clutch increases when the sum of the output torque is increased as shown in Figure 34. There are two types of pre-load strategies: One is the sum of pre-load and increasing load, the other is the maximum of pre-load and increasing load. The slope of each line is the Torque Bias Ratio (TBR) defined by the following equation:

$$\mathrm{TBR} = \frac{\text{Non– slipping side torque}}{\text{Slipping side torque}} \tag{35}$$

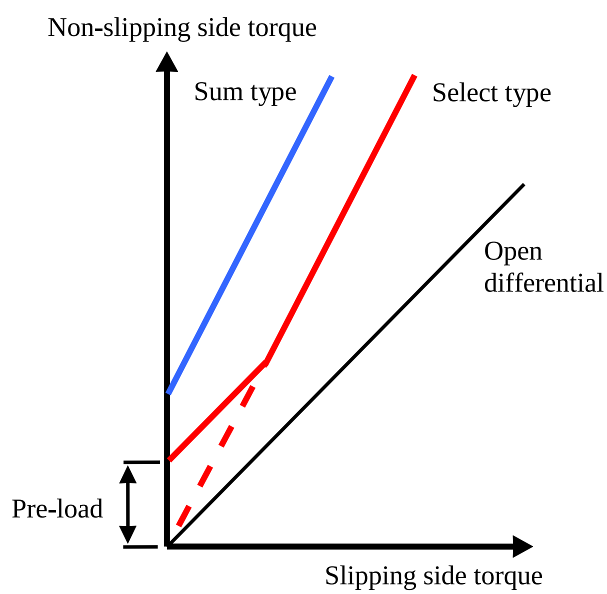

Figure 34: Definition of torque bias ratio (TBR).

TBR can be different between during the acceleration and deceleration with engine braking – therefore TBR is defined separately for each case.

Another expression for LSD's characteristics is Lock Ratio (L.R.), which is defined by the following equation:

$$\text{L.R.} = \frac{(\text{Non slipping side torque}) - (\text{Slipping side torque})}{(\text{Non slipping side torque}) + (\text{Slipping side torque})} = \frac{\textit{Torque differential}}{\textit{Sum of output torque}} \tag{36}$$

Figure 35 shows the LSD's characteristics using the lock ratio. As shown in this figure, when the sum of the output torque increases, the torque differential increases.

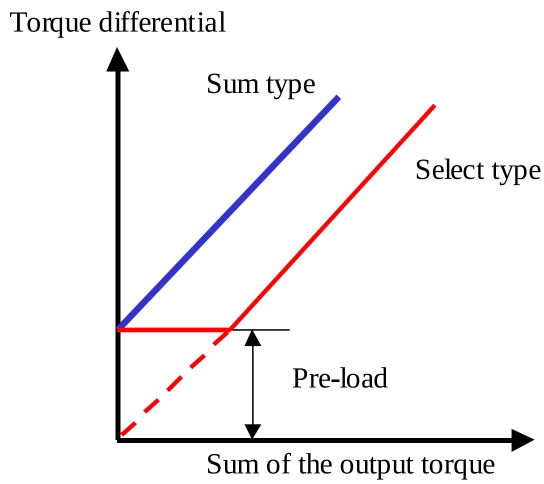

Figure 35: Definition of Lock Ratio (L. R.).

The LSDs over front and rear differentials are expressed by TBR and the center differential is expressed by L.R.

Yaw Control Differential

The Yaw Control Differential employs two clutches with reduction gears in parallel over a differential (Figure 36). (This configuration, developed by Honda Formula1, was described by Peter Wright [2].) Each output shaft from the differential feeds back torque through a reduction gear to a clutch connected to the output shaft from the opposite side of the differential. With the clutches released, the feedback paths are disconnected and the system functions as a normal free differential. If either clutch is loaded, torque is transferred from one side to the other, bypassing the differential. The two shafts are forced to run at different speeds due to the reduction gear. Selective control of the left- or right-side clutch thus allows the vehicle yaw motion to be controlled. Use of this type of system at the transfer case allows control over the torque distribution between front and rear wheels.

Twin-Clutch

The Twin-Clutch system is available at the front and/or rear axles. The system involves a gearbox in the middle of the axle and two clutches between each wheel and the gearbox (Figure 37).

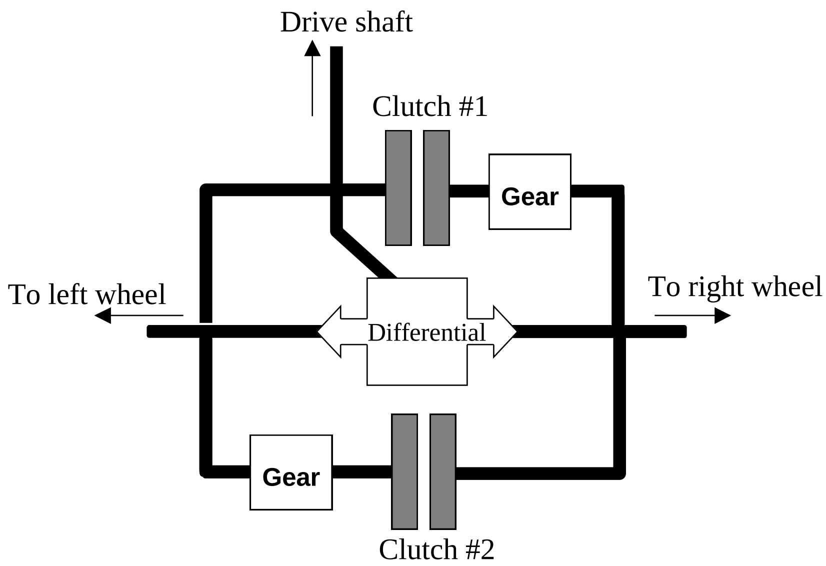

Figure 36 Yaw control differential (front or rear).

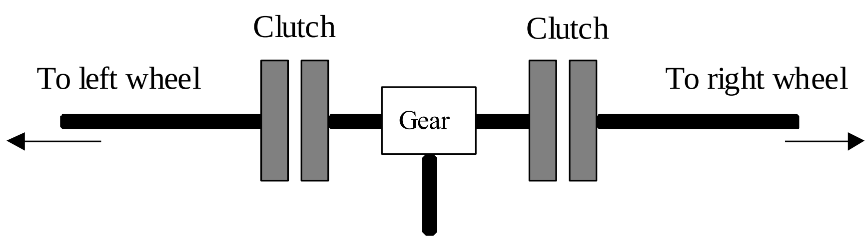

Figure 37: Twin-clutch (front or rear).

If the clutch is disconnected (free), the drive torque is not transmitted to the wheel. The clutch also can include a viscous effect, which transmits a torque to the wheel determined by the speed differential between the gearbox output and wheel.

In general, the twin-clutch system is adopted for either front or rear axle in the part-time 4WD, whose transfer case may be locked all the time (Figure 38). The system is essentially a front-wheel drive vehicle when the both of twin-clutches in rear are free. Whenever the rear twin-clutches are engaged, the system becomes a Part-Time 4WD. The right and left clutches in the twin-clutch system can be controlled different ways to affect the vehicle yaw motion.

Transfer Case

In the 4-wheel drive model, the transmission output torque is distributed to the front and rear drive shafts through the transfer case. Torque transfer from the transfer case to the drive shafts is explained as follows.

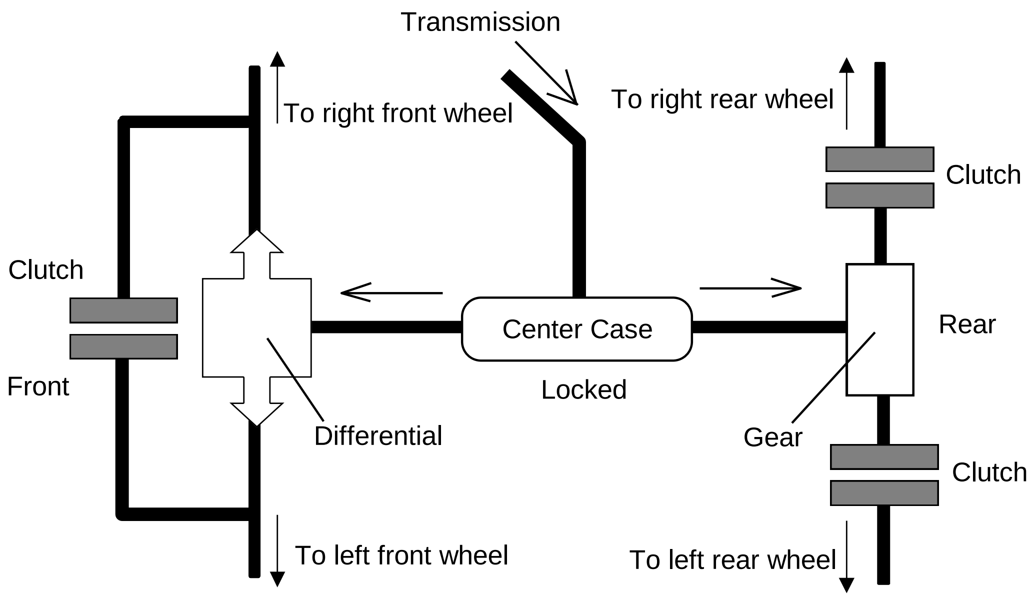

Figure 38: An example setting - front LSD/rear twin clutch in the part-time 4-wheel drive.

Locked (Part-Time 4WD)

When the transfer case is locked, the transmission output shaft angular speed ω_g is defined by the rotational speed of front and rear drive shafts, such as:

$$\omega_g = 0.5 \times (\omega_{gF} + \omega_{gR}) \tag{37}$$

Transmission output shaft rotation angle ϕ_g is defined by the rotational angle of front and rear drive shafts, such as:

$$\phi_g = 0.5 \times (\phi_{gF} + \phi_{gR}) \tag{38}$$

Torque distribution to the front and rear drive shafts are as follows. The front drive shaft torque is:

$$\begin{aligned} T_{gF} &= 0.5 \times T_g \times N_{trcase} \times E_{trcase} - T_{lock\_trcase} \quad (T_{tcout}{}^* \geq 0) \quad or \\ T_{gF} &= 0.5 \times T_g \times N_{trcase} / E_{trcase\_rev} - T_{lock\_trcase} \quad (T_{tcout}{}^* < 0) \end{aligned} \tag{39}$$

where T_{lock_trcase} is the torque due to torsion of front and rear axles, such as:

$$T_{lock\_trcase} = K_{lock\_TC} \times (\phi_{gF} - \phi_{gR}) + D_{lock\_TC} \times (\omega_{gF} - \omega_{gR}) \tag{40}$$

The rear drive shaft torque is:

$$\begin{aligned} T_{gR} &= T_g \times N_{trcase} \times E_{trcase} - T_{gF} \quad (T_{tcout}{}^* \geq 0) \quad or \\ T_{gR} &= T_g \times N_{trcase} / E_{trcase\_rev} - T_{gF} \quad (T_{tcout}{}^* < 0) \end{aligned} \tag{41}$$

Free or Viscous Coupling (Full-Time 4WD)

When the transfer case is not locked, the transmission output shaft angular speed ω_g is defined by the rotational speed of front and rear drive shafts and gear ratio of the transfer case, N_{trcase}, such as:

$$\omega_g = \{(1 - T_{bias\_to\_rear}) \times \omega_{gF} + T_{bias\_to\_rear} \times \omega_{gR}\} \times N_{trcase} \tag{42}$$

Transmission output shaft rotation angle ϕ_g is defined by the rotational angle of front and rear drive shafts and gear ratio of the transfer case, N_{trcase}, such as:

$$\phi_g = \{(1 - T_{bias\_to\_rear}) \times \phi_{gF} + T_{bias\_to\_rear} \times \phi_{gR}\} \times N_{trcase} \tag{43}$$

Torque distribution to front and back is as follows. The front drive shaft torque is:

$$\begin{aligned} T_{gF} &= (1 - T_{bias\_to\_rear}) \times T_g \times N_{trcase} \times E_{trcase} + 0.5 \times f_{trcase}(\omega_{gF} - \omega_{gR}) - T_{clutch\_trcase} \quad (T_{tcout}{}^{*} \geq 0) \quad \textit{or} \\ T_{gF} &= (1 - T_{bias\_to\_rear}) \times T_g \times N_{trcase} / E_{trcase\_rev} + 0.5 \times f_{trcase}(\omega_{gF} - \omega_{gR}) - T_{clutch\_trcase} \quad (T_{tcout}{}^{*} < 0) \end{aligned} \tag{44}$$

where E_{trcase} is the efficiency of transfer case for when the engine drives the wheel while E_{trcase_rev} is the efficiency for when the wheels drive the engine. The table function, f_{trcase}, is the torque difference between the front and rear, as the function of speed differential. $T_{bias\_to\_rea}$ is the torque bias to the rear wheels, whose range of value is between 0 and 1. T_{clutch_trcase} is the torque at the transfer case clutch, which is described in the next sub-section.

The torque transferred to the rear drive shaft is:

$$\begin{aligned} T_{gR} &= T_g \times N_{trcase} \times E_{trcase} - T_{gF} \quad (T_{tcout}{}^{*} \geq 0) \quad \textit{or} \\ T_{gR} &= T_g \times N_{trcase} / E_{trcase\_rev} - T_{gF} \quad (T_{tcout}{}^{*} < 0) \end{aligned} \tag{45}$$

Mechanical Clutch (LSD)

T_{clutch_trcase} is the torque of a mechanical clutch, which is calculated by the different equations in the cases of locked and slipping clutches. Firstly, those states are distinguished and switch to the other state according to the following operating conditions.

$$\begin{aligned} &\text{if currently slipping then} \\ &\quad \text{If } \mathrm{abs}(T_{clutch\_trcase\_cap}) > \mathrm{abs}(T_{clutch\_trcase\_lock}) \quad AND \quad (d\omega_{clutch\_trcase} \times d\omega_{clutch\_trcase\_old}) < 0.0 \\ &\quad \text{then} \quad \text{'chage to locked'} \quad \text{else} \quad \text{'keep slipping'} \\ &\text{else (currently locked)} \\ &\quad \text{If } \mathrm{abs}(T_{clutch\_trcase\_cap}) > \mathrm{abs}(T_{clutch\_trcase}) \\ &\quad \text{then} \quad \text{'keep locked'} \quad \text{else} \quad \text{'change to slipping'} \end{aligned} \tag{46}$$

Where $d\omega_{clutch\_trcase}$ is the speed differential between front and rear driveshaft (ω_{gF}-ω_{gR}) and $d\omega_{clutch\_trcase\_old}$ is $d\omega_{clutch\_trcase}$ from one calculation step ago. The term of the condition "($d\omega_{clutch\_trcase\_old}$ x $d\omega_{clutch\_trcase}$) < 0.0" represents that the speed differential of the clutch reverses to the other direction. $T_{clutch\_trcase\_cap}$ denotes the torque capacity of clutch, which is defined by the table function as:

$$T_{clutch\_trcase\_cap} = f_{clutch\_trcase\_cap}(Clutch\_trcase\_displacement) \tag{47}$$

Clutch_trcase_displacement is the input value (0 – 1) from the external control or from the other table, which is the torque sensitive limiting slip, namely, *LSD*. $T_{clutch\_trcase\_lock}$ denotes the theoretically calculated torque load on the locked clutch, whose value is calculated by:

$$T_{clutch\_trcase\_lock} = \frac{M_{gF} - M_{gR} \cdot \dfrac{I_{axle\_F}}{I_{axle\_R}}}{1 + \dfrac{I_{axle\_F}}{I_{axle\_R}}} \tag{48}$$

where:

$$\begin{aligned}
M_{gF} &= (M_{y_load_LF} + M_{y_load_RF}) / N_{diff_F} \\
M_{gR} &= (M_{y_load_LR} + M_{y_load_RR}) / N_{diff_R} \\
I_{axle_F} &= \{(2I_{wF} + I_{axle_LF} + I_{axle_RF}) / N_{diff_F}{}^2\} + I_{shaft_F} \\
I_{axle_R} &= \{(2I_{wR} + I_{axle_LR} + I_{axle_RR}) / N_{diff_R}{}^2\} + I_{shaft_R}
\end{aligned} \tag{49}$$

M_{y_load} is the torque load at each wheel that involves the torque due to tire force and moment and brake torque.

Overall, if the torque capacity ($T_{clutch\_trcase\_cap}$) is bigger than the torque load ($T_{clutch\_trcase\_lock}$) and the speed differential between the front and rear driveshaft is reversed to the other direction then the clutch is locked. On the other hand, when the clutch locked, if the clutch torque ($T_{clutch\_trcasep}$: described below) exceeds the torque capacity ($T_{clutch\_trcase\_cap}$), the clutch starts to slip.

> **Note** The derivation of the torque load on the locked clutch is described in the Appendix (page 56).

When the clutch is locked the clutch torque is:

$$T_{clutch\_trcase} = K_{lock\_trcase} \times (\phi_{gF} - \phi_{gR}) + D_{lock\_trcase} \times (\omega_{gF} - \omega_{gR}) \tag{50}$$

When the clutch is slipping:

$$T_{clutch\_trcase} = \mathrm{sign}\left(T_{clutch\_trcase\_cap}, d\omega_{clutch\_trcase}\right) \tag{51}$$

where `sign` is the sign function that the sign of the first term ($T_{clutch\_trcase\_cap}$) depends on the second term ($d\omega_{clutch\_trcase}$). When $d\omega_{clutch\_trcase}$ is positive, T_{clutch_trcase} is also positive in this case.

Powertrain: Transfer Case screen

The transfer case parameters and table functions are defined on the **Powertrain: Transfer Case screen (**Figure 39) that is linked to a Powertrain screen that supports two or more axles.

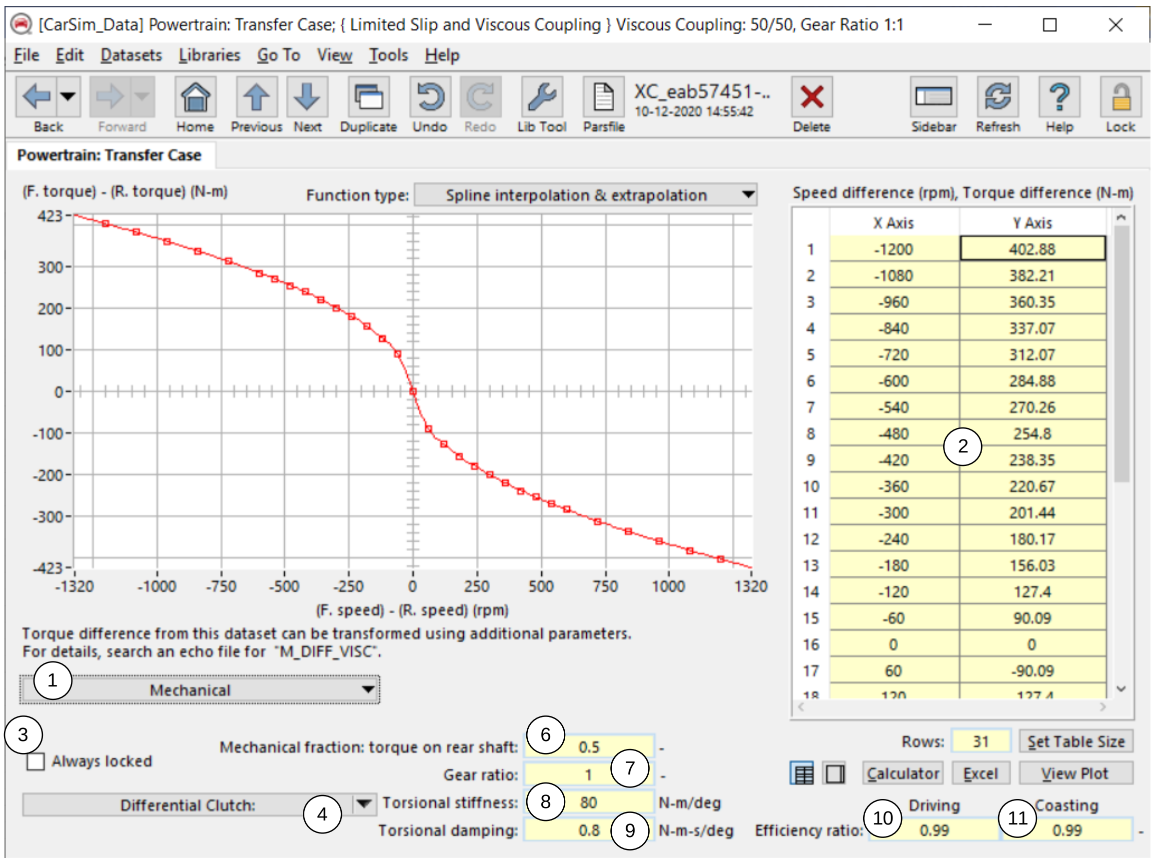

Figure 39: Screen for a transfer case (mechanical setting).

All parameters and data tables involved in this screen adopt the same keywords as the front and rear differential screens. However, those keywords are distinguished among those screens using the differential index `IDIFF`: 1 is the front differential, 2 is the rear differential, and 3 is the transfer case.

(1) Drop-down list for choosing among three options for distributing drive torque (Figure 40):

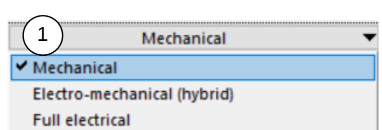

Figure 40. Options for distributing drive torque.

1. **Mechanical**: drive torque from the transmission output is mechanically distributed between the front and rear drive shafts based on the mechanical fraction (6). This option is used for an internal-combustion powertrain or electric/hybrid powertrain with a mechanical transfer case.

2. **Electro-mechanical (hybrid)**: an additional electrical torque distribution parameter field 5 appears (Figure 41), in which electric motor torque demand is electrically distributed between the front and rear motors (e-AWD). The drive torque from the engine is still mechanically distributed between the front and rear drive shafts based on the mechanical fraction 6. This option is used for a hybrid powertrain with multiple electric motors placed on the front and rear drive axles without any mechanical connection between them.

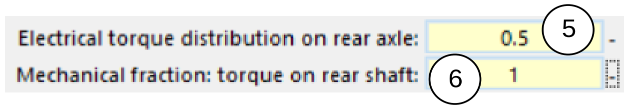

Figure 41. Additional data field for e-AWD.

3. **Full electrical**: electric motor torque demand is electrically distributed between the front and rear motors (e-AWD) based on the electrical torque distribution parameter 5. With this selection, the mechanical fraction parameter 6, Always locked checkbox 3, and the differential clutch dataset link 4 are all hidden.

> **Note:** For more details about the Hybrid or Electric system, please see the separate document *Powertrain for Electric and Hybrid Electric Vehicles (BEV/HEV)*.

2 Torque differential as a function of speed differential (root keyword = `M_DIFF_VISC(IDIFF)`). This table and the corresponding plot are displayed only when the **Always locked** box 3 is not checked. (This table is not used for simulating a locked differential.)

3 **Always locked** box (keyword = `OPT_LOCKED_DIFF(IDIFF)`). Check this box to specify a locked differential. When checked, the viscous differential table and plot are hidden. The data link for an optional mechanical clutch 4 is also hidden when the differential is always locked. This box also is hidden if the option **Full electrical** is selected in 1.

4 Link to a **Powertrain: Differential Clutch** dataset. A clutch connects the front and rear output shafts unless the differential is always locked (as indicated by the checkbox 3). Alternatively, link to a **Powertrain: Limited Slip Differential for Center Case**, or a **Powertrain: Yaw Control Differential.** This link is hidden if the option **Full electrical** is selected in 1.

5 Electrical torque distribution on rear axle (keyword = `R_REAR_MOTOR_BIAS(IDIFF)`). This ratio is normally 0.5, causing the electric motor torque demand to be split evenly between the front and rear motors. However, you can use a different value to simulate asymmetrical motor torque distribution. (The range of acceptable values is 0 to 1). This field is hidden if the option **Mechanical** is selected in 1.

6 Mechanical fraction: torque on rear shaft (keyword = `R_REAR_BIAS(IDIFF)`). This ratio is normally 0.5, causing the drive torque from the transmission output to be split evenly to the front and rear drive shafts. However, you can use a different value to simulate asymmetric differentials. (The range of acceptable values is 0 to 1). This field is hidden if the differential is always locked 3 or the option **Full electrical** is selected in 1.

(7) Gear ratio of the transfer case (keyword = `R_GEAR_DIFF(IDIFF)`). This is the input shaft spin rate divided by the output spin rate.

(8) Torsional stiffness (keyword = `LOCKED_DIFF_K(IDIFF)`). Connecting the front and rear drive shafts with a torsional spring and damper simulates a locked differential. This is the stiffness of the spring.

(9) Torsional damping (keyword = `LOCKED_DIFF_DAMP(IDIFF)`). Connecting the front and rear drive shafts with a torsional spring and damper simulates a locked differential. This is the linear damping constant.

(10) Driving efficiency ratio (keyword = `R_EFF_F_DIFF(IDIFF)`). The torque of incoming shaft is multiplied by this coefficient when obtaining torques applied to the wheels under normal acceleration (Equations 39, 41, 44 and 45.)

(11) Coasting efficiency ratio (keyword = `R_EFF_R_DIFF(IDIFF)`). The torque of incoming shaft is divided by this coefficient when obtaining torques applied to the wheels under deceleration (engine drag) conditions (Equations 39, 41, 44 and 45.)

Differential Gear

The same differential gear model is used in the front and rear axle. The following description uses the notations for the front axle.

Transmission output shaft (or transfer case output in 4WD) angular speed ω_g is defined by the rotational speed of right and left driving wheel and gear ratio N_{diff_F}, such as:

$$\omega_g = 0.5 \times (\omega_{whLF} + \omega_{whRF}) \times N_{diff\_F} \tag{52}$$

Transmission output shaft rotation angle ϕ_g is defined by the rotational angle of right and left driving wheel and gear ratio N_{diff_F}, such as:

$$\phi_g = 0.5 \times (\phi_{whLF} + \phi_{whRF}) \times N_{diff\_F} \tag{53}$$

Torque Distribution (Always Locked)

When the differential system is locked, the torque transferred to the left wheel is:

$$\begin{aligned} M_{y\_LF} &= 0.5 \times (T_g \times N_{diff\_F} \times E_{diff\_F}) - T_{lock\_F} \quad (T_{tcout}^* \geq 0) \quad \textit{or} \\ M_{y\_LF} &= 0.5 \times (T_g \times N_{diff\_F} / E_{diff\_F\_rev}) - T_{lock\_F} \quad (T_{tcout}^* < 0) \end{aligned} \tag{54}$$

where E_{diff_F} is the efficiency of the differential gear for when the engine drives the wheel while $E_{diff\_F\_rev}$ is the efficiency for when the wheels drive the engine. T_{lock_F} is the torque due to torsion of front axle, such as:

$$T_{lock\_F} = K_{lock\_F} \times (\phi_{whLF} - \phi_{whRF}) + D_{lock\_F} \times (\omega_{whLF} - \omega_{whRF}) \tag{55}$$

The torque to the right wheel is:

$$M_{y\_RF} = T_g \times N_{diff\_F} \times E_{diff\_F} - M_{y\_LF} \quad (T_{tcout}{}^{*} \geq 0) \quad or$$
$$M_{y\_RF} = T_g \times N_{diff\_F} / E_{diff\_F\_rev} - M_{y\_LF} \quad (T_{tcout}{}^{*} < 0) \tag{56}$$

Torque Distribution (Free Differential or Viscous Coupling)

Torque is transferred to the left wheel through either a free or a viscous coupling differential system:

$$M_{y\_LF} = 0.5 \times \{T_g \times N_{diff\_F} \times E_{diff\_F} + f_{lsd}(\omega_{whLF} - \omega_{whRF})\} - T_{clutch\_ciff} \quad (T_{tcout}{}^{*} \geq 0) \quad or$$
$$M_{y\_LF} = 0.5 \times \{T_g \times N_{diff\_F} / E_{diff\_F\_rev} + f_{lsd}(\omega_{whLF} - \omega_{whRF})\} - T_{clutch\_ciff} \quad (T_{tcout}{}^{*} < 0) \tag{57}$$

The table function f_{lsd} is the torque difference between the left and right, as the function of speed differential. T_{clutch_diff} is the torque at the differential clutch, which is described in the next sub-section.

The torque transferred to the right wheel is:

$$M_{y\_RF} = T_g \times N_{diff\_F} \times E_{diff\_F} - M_{y\_LF} \quad (T_{tcout}{}^{*} \geq 0) \quad or$$
$$M_{y\_RF} = T_g \times N_{diff\_F} / E_{diff\_F\_rev} - M_{y\_LF} \quad (T_{tcout}{}^{*} < 0) \tag{58}$$

Mechanical Clutch (LSD)

T_{clutch_diff} is the torque of the mechanical clutch, which is calculated by the different equations in the cases of locked and slipping clutches. Firstly, those states are distinguished and switch to other state by the following operating conditions.

$$\begin{aligned}
&\text{if currently slipping then} \\
&\quad \text{If } \mathrm{abs}(T_{clutch_diff_cap}) > \mathrm{abs}(T_{clutch_diff_lock}) \quad AND \quad (d\omega_{clutch_diff} \times d\omega_{clutch_diff_old}) < 0.0 \\
&\quad \text{then} \quad \text{'chage to locked'} \quad \text{else} \quad \text{'keep slipping'} \\
&\text{else (currently locked)} \\
&\quad \text{If } \mathrm{abs}(T_{clutch_diff_cap}) > \mathrm{abs}(T_{clutch_diff}) \\
&\quad \text{then} \quad \text{'keep locked'} \quad \text{else} \quad \text{'change to slipping'}
\end{aligned} \tag{59}$$

Where $d\omega_{clutch\_diff}$ is the speed differential between left and right wheels (ω_{whLF}-ω_{whRF}) and $d\omega_{clutch\_diff\_old}$ is $d\omega_{clutch\_diff}$ from one calculation step ago. The term of the condition "($d\omega_{clutch\_diff\_old}$ x $d\omega_{clutch\_diff}$) < 0.0" represents that the speed differential of the clutch reverses to the other direction. $T_{clutch\_diff\_cap}$ denotes the torque capacity of clutch, which is defined by the table function as:

$$T_{clutch\_diff\_cap} = f_{clutch\_diff\_cap}(Clutch\_diff\_displacement) \tag{60}$$

Clutch_diff_displacement is the input value (0 – 1) from the external control or from the other table, which is the torque sensitive limiting slip, namely, *LSD*. $T_{clutch\_diff\_lock}$ denotes the theoretically calculated torque load on the locked clutch, whose value is calculated by:

$$T_{clutch\_diff\_lock} = \frac{M_{y\_load\_LF} - M_{y\_load\_RF} \cdot \dfrac{I_{axle\_LF} + I_{wF}}{I_{axle\_RF} + I_{wR}}}{1 + \dfrac{I_{axle\_LF} + I_{wF}}{I_{axle\_RF} + I_{wR}}} \tag{61}$$

where M_{y_load} is the torque load at each wheel that involves the torque due to tire force and moment and brake torque.

Overall, if the torque capacity ($T_{clutch\_diff\_cap}$) is bigger than the torque load ($T_{clutch\_diff\_lock}$) and the speed differential between the left and right wheels is reversed to the other direction then the clutch is locked. On the other hand, if the clutch torque (T_{clutch_diff} : described below) exceeds the torque capacity ($T_{clutch\_diff\_cap}$), the clutch starts to slip.

> **Note** The derivation of the torque load on the locked clutch is described in the Appendix (page 56).

When the clutch is locked the clutch torque is:

$$T_{clutch\_diff} = K_{lock\_F} \times (\phi_{whLF} - \phi_{whRF}) + D_{lock\_F} \times (\omega_{whLF} - \omega_{whRF}) \tag{62}$$

When the clutch is slipping:

$$T_{clutch\_diff} = \text{sign}\left(T_{clutch\_diff\_cap}, d\omega_{clutch\_diff}\right) \tag{63}$$

where `sign` is the sign function that the sign of the first term ($T_{clutch\_diff\_cap}$) depends on the second term ($d\omega_{clutch\_diff}$). When $d\omega_{clutch\_diff}$ is positive, T_{clutch_diff} is also positive in this case.

Differential Axle with One or Two Electric Motors

CarSim and TruckSim support two different electrified differential axles: one has an electric motor on the center drive shaft and the other has two motors on both sides of the wheel shafts, shown in Figure 42 and Figure 43, respectively.

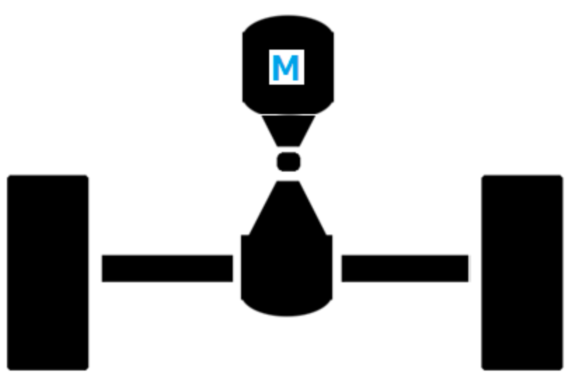

Figure 42: Differential axle with one electric motor on center drive shaft.

The differential axle with one electric motor (Figure 42) has a conventional differential gear which can be free, locked, viscous and/or have a torque sensitive clutch. The electric motor is connected to the center drive shaft and the motor torque is electrically controlled.

The other electrified differential axle (Figure 43) has two electric motors which are directly connected with both sides of the wheel shafts. In this axle, there is no conventional differential gear. However, there can be a mechanical clutch between the two motors to limit or lock the speed differential and each motor's output torque is electrically controlled individually.

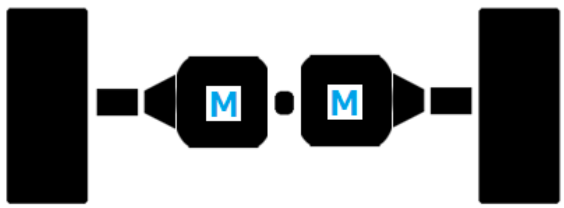

Figure 43: Axle with two electric motors on both sides of wheel shafts.

User Settings

These differential parameters and table functions are defined on the screen shown in Figure 44.

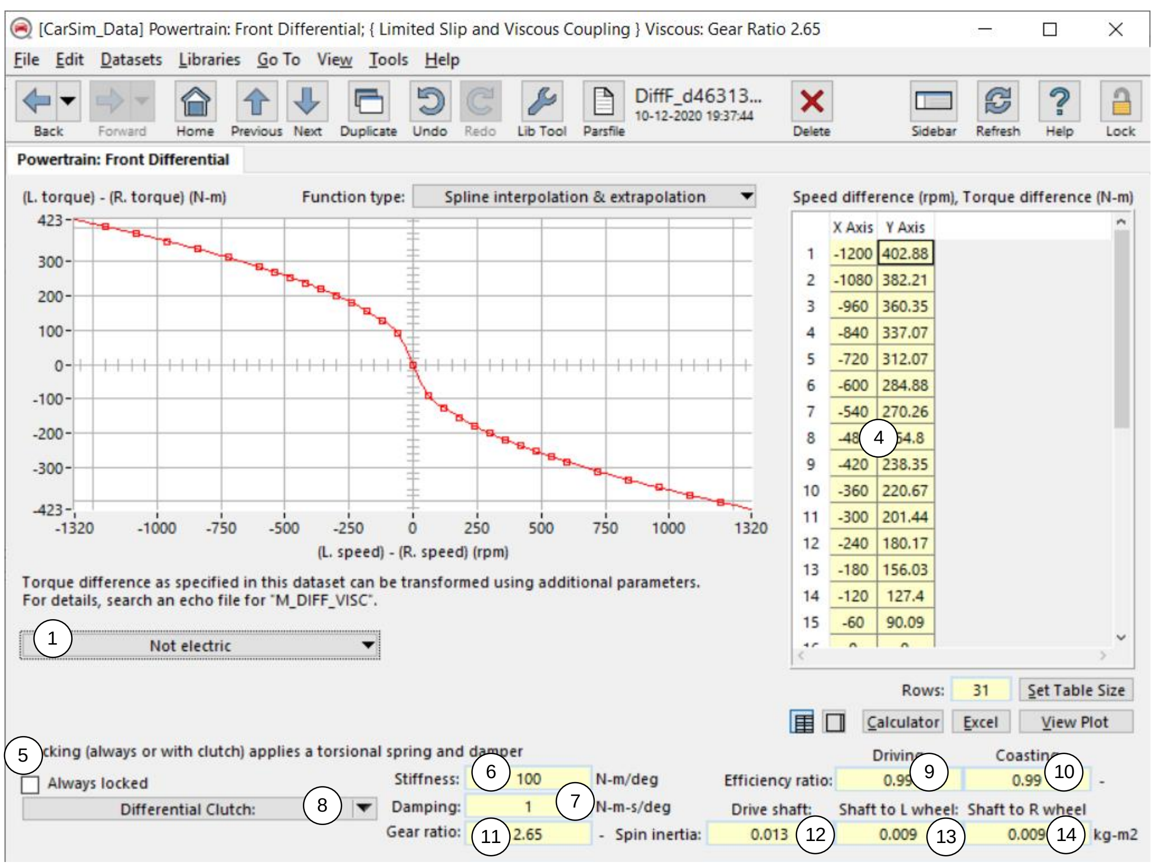

Figure 44: Screen for a differential gear (not electric).

All parameters and data tables involved in this screen adopt the same keywords as the front and rear differential screens. However, those keywords are distinguished among those screens using the differential index `IDIFF`: 1 is the front differential, 2 is the rear differential, and 3 is the transfer case.

① Drop-down list for choosing among three types of definitions (Figure 45):

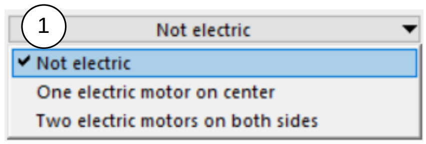

Figure 45. Three options for electric motors on differentials.

1. **Not electric**: this selection is for a conventional mechanical differential gear without electric motor.
2. **One electric motor on center**: a dataset link for an electrical motor ② appears (Figure 46) and the electric motor torque characteristics are specified. The location of the electric motor is in the center drive shaft as shown in Figure 42.

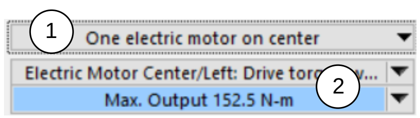

Figure 46. Link for an electric motor at the differential center.

3. **Two electric motors on both sides**: two dataset links for the electrical motors ② appear and the electric motor torque characteristics are specified for each side (Figure 47). Also, an additional checkbox ③ appears to specify the body reacting to the motor torques (e.g., the spinning and non-spinning parts of the unsprung mass for an independent suspension). The diagrammatic figure is shown in Figure 43.

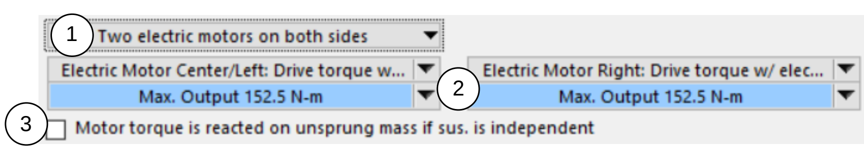

Figure 47. Additional data settings for electrically driving wheels.

Note: For more details about the Hybrid or Electric system, please see the separate document *Powertrain for Electric and Hybrid Electric Vehicles (BEV/HEV).*

② Link to a **Powertrain: Electric Motor Torque** dataset. The left dataset link is for the motor on the center drive shaft if one electric motor is selected in ①. If the option for two electric motors is selected, the left and right dataset are applied to the left-side and right-side wheels, respectively.

3 Motor torque reaction checkbox (keyword = `OPT_WHEEL_MOTOR_REACTION(IDIFF)`). Check this box to specify that the motor torque is reacted by the unsprung mass if the suspension type is independent. For example, if the motors are located on the wheel carriers or wheel hubs (i.e., in-wheel motor), the box should be checked. On the other hand, if the motors are located on the chassis, the box should be unchecked.

Note In case of a solid-axle suspension, the motor torque is reacted by the unsprung mass regardless of the setting of this checkbox.

4 Torque differential as a function of speed differential (root keyword = `M_DIFF_VISC(IDIFF)`). This table and the corresponding plot are displayed only when the **Always locked** box 5 is not checked. (The table is not used for simulating a locked differential.)

5 **Always locked** box (keyword = `OPT_LOCKED_DIFF(IDIFF)`). Check this box to specify a locked differential. When checked, the viscous differential table and plot are hidden. The data link for an optional mechanical clutch 8 is also hidden when the differential is always locked.

6 Torsional stiffness (keyword = `LOCKED_DIFF_K(IDIFF)`). Connecting the left and right wheels with a torsional spring and damper simulates a locked differential. This is the stiffness of the spring.

7 Torsional damping (keyword = `LOCKED_DIFF_DAMP(IDIFF)`). Connecting the left and right wheels with a torsional spring and damper simulates a locked differential. This is the linear damping constant.

8 Link to a **Powertrain: Differential Clutch** dataset, a **Powertrain: Limited Slip Differential (Front or Rear)** dataset, or a **Powertrain: Yaw Control Differential** dataset. The clutches connect the left and right output shafts unless the differential is always locked (as indicated by the checkbox 5).

9 Driving efficiency ratio (keyword = `R_EFF_F_DIFF(IDIFF)`). The torque of the drive shaft is multiplied by this coefficient when obtaining torques applied to the wheels under normal acceleration (Equations 54, 56, 57 and 58.)

10 Coasting efficiency ratio (keyword = `R_EFF_R_DIFF(IDIFF)`). The torque of the drive shaft is divided by this coefficient when obtaining torques applied to the wheels under deceleration (engine drag) conditions (Equations 54, 56, 57 and 58.)

11 Gear ratio of the front differential (keyword = `R_GEAR_DIFF(IDIFF)`). This is the input shaft spin rate divided by the average output spin rate of the two half-shafts.

12 Spin inertia of the drive shaft to the front differential (keyword = `IDS(IDIFF)`).

13 Spin inertia of the front differential half-shaft to the left wheel (keyword = `IHS_L(IDIFF)`).

14 Spin inertia of the front differential half-shaft to the right wheel (keyword = `IHS_R(IDIFF)`).

Import Variables

Import variables offer a method to control aspects of the powertrain model via equations or external software (e.g., supplying engine torque values externally). Typically, internal variables used by the model can be combined with user-defined values according to one of three user-specified modes: `ADD`, `REPLACE`, and `MULTIPLY`.

> **Note** For more information on Import variables, see the *VS Commands Reference Manual*.

Due to the modular nature of the powertrain model, not all import modes (`ADD/REPLACE/MULTIPLY`) are available in all model configurations. Some Import variables are specialized and only have an effect in specific contexts.

Table 8 lists all powertrain Import variables that can have different behavior than the standard `ADD/REPLACE/MULTIPLY` modes.

Table 8. Powertrain Import variables with special behavior.

Import Variable	**Description of Behavior**
`IMP_AV_D3_R` (et al.)	This import keyword is affected by the modular powertrain. When `[OPT_DIFF_INTERNAL=0]`, the import behavior is `REPLACE`. When `[OPT_DIFF_INTERNAL=1]`, this import has no effect.
`IMP_MY_OUT_D2_L` (et al.)	This import keyword is affected by the modular powertrain. When `[OPT_DIFF_INTERNAL=0]`, the import behavior is `REPLACE`. When `[OPT_DIFF_INTERNAL=1]`, the import behaves normally for `ADD`, `MULTIPLY`, and `REPLACE`.
`IMP_M_OUT_D3_R` (et al.)	This import keyword is affected by the modular powertrain. When `[OPT_DIFF_INTERNAL=0]`, the import behavior is `REPLACE`. When `[OPT_DIFF_INTERNAL=1]`, the import behaves normally for `ADD`, `MULTIPLY`, and `REPLACE`.
`IMP_ESC_ENGINE_` `CON_STATE`	This import keyword uses integer input only `[0, 1, 2]` to switch between modes. All import behavior is `REPLACE`.

Table 8. Powertrain Import variables with special behavior.

Import Variable	Description of Behavior
IMP_MENGINE_ESC_REQUEST	This import keyword has no internal equivalent and is only used in tandem with IMP_ESC_ENGINE_CON_STATE. All import behavior is REPLACE.
IMP_MENGINE	This import keyword is affected by the modular powertrain. When [OPT_ENGINE_INTERNAL=0], the import behavior is REPLACE. When [OPT_ENGINE_INTERNAL=1], the import behaves normally for ADD, MULTIPLY, and REPLACE.
IMP_AV_ENG	This import keyword is affected by the modular powertrain. When [OPT_HEV=1], the import behaves normally for ADD, MULTIPLY, and REPLACE. When [OPT_ENGINE_INTERNAL=0], the import behavior is REPLACE. When [OPT_ENGINE_INTERNAL=1], this import has no effect.
IMP_INERTIA_TR	This import keyword is affected by the modular powertrain. When [OPT_TRANS_INTERNAL=0], the import behavior is REPLACE. When [OPT_TRANS_INTERNAL=1], the import behaves normally for ADD, MULTIPLY, and REPLACE.
IMP_R_EFF_TR	This import keyword is affected by the modular powertrain. When [OPT_TRANS_INTERNAL=0], the import behavior is REPLACE. When [OPT_TRANS_INTERNAL=1], the import behaves normally for ADD, MULTIPLY, and REPLACE.
IMP_AV_TC	This import keyword is affected by the modular powertrain. When [OPT_TRANS_INTERNAL=0], the import behavior is REPLACE. When [OPT_TRANS_INTERNAL=1], this import has no effect.

Table 8. Powertrain Import variables with special behavior.

Import Variable	**Description of Behavior**
IMP_M_OUT_TR	This import keyword is affected by the modular powertrain. When [OPT_TRANS_INTERNAL=0], the import behavior is REPLACE. When [OPT_TRANS_INTERNAL=1], the import behaves normally for ADD, MULTIPLY, and REPLACE.
IMP_MENG_REACT	This import keyword is affected by the modular powertrain. When [OPT_PWR_CPL_INTERNAL=0], the import behavior is REPLACE. When [OPT_PWR_CPL_INTERNAL=1 and OPT_CLUTCH=0], the import behavior is ADD. When [OPT_PWR_CPL_INTERNAL=1 and OPT_CLUTCH=1], the import behaves normally for ADD, MULTIPLY, and REPLACE. When [OPT_PWR_CPL_INTERNAL=1 and OPT_CLUTCH=2], the import behavior is ADD.
IMP_M_OUT_TC	This import keyword is affected by the modular powertrain. When [OPT_PWR_CPL_INTERNAL=0], the import behavior is REPLACE. When [OPT_PWR_CPL_INTERNAL=1], the import behavior is ADD.
IMP_M_DIFF_D3 (et al.)	This import keyword is affected by the modular powertrain. For HEV axle motors, the import behavior is REPLACE. Otherwise, the import behaves normally for ADD, MULTIPLY, and REPLACE.
IMP_CLUTCH_L1 (et al.) IMP_CLUTCH_R1 (et al.)	These import keywords are affected by the modular powertrain. For Twin Clutch differentials, the import behavior is REPLACE. For other differentials, the import has no effect.

Table 8. Powertrain Import variables with special behavior.

Import Variable	Description of Behavior
`IMP_CLUTCH_D1` (et al.) `IMP_CLT_D1_2` (et al.)	These import keywords are affected by the modular powertrain. For Yaw Control differentials, the import behavior is `REPLACE`. Otherwise, the import behaves normally for `ADD`, `MULTIPLY`, and `REPLACE`.

Driving Wheel Calculation

As described in the Transmission section (page 25), the driveline inertia is divided into two parts at the middle of the transmission. One side (engine side) has its own degree of freedom and its inertia is used to calculate the transmission input speed. The inertia of the other side (wheel side) is used to calculate the wheel speeds.

If a transfer case is involved (in the case of four-wheel drive), the moments of inertia of the front and rear driveshafts are:

$$\begin{aligned} I_{trans\_drv\_F} &= (1 - T_{bias\_to\_rear}) \times 0.5 I_{trans} \times N_{trcase}{}^2 + I_{shaft\_F} \\ I_{trans\_drv\_R} &= T_{bias\_to\_rear} \times 0.5 I_{trans} \times N_{trcase}{}^2 + I_{shaft\_R} \end{aligned} \tag{64}$$

If the powertrain does not involve a transfer case (either front-wheel drive or rear-wheel drive), the moment of inertia of a driveshaft is:

$$\begin{aligned} I_{trans\_drv\_F} &= 0.5 I_{trans} + I_{shaft\_F} \\ I_{trans\_drv\_R} &= 0.5 I_{trans} + I_{shaft\_R} \end{aligned} \tag{65}$$

The angular acceleration of each wheel should be calculated with the consideration of driveshaft inertia. For example, if an open differential is adopted on the front axle, the left and right wheel acceleration is:

$$\begin{aligned} \dot{\omega}_{whLF} &= \frac{0.5 N_{diff\_F} (T_g - \dot{\omega}_g I_{trans\_drv\_F}) + M_{y\_load\_LF}}{I_{wF} + I_{axle\_LF}} \\ \dot{\omega}_{whRF} &= \frac{0.5 N_{diff\_F} (T_g - \dot{\omega}_g I_{trans\_drv\_F}) + M_{y\_load\_RF}}{I_{wF} + I_{axle\_RF}} \end{aligned} \tag{66}$$

where $M_{y\_load\_LF}$ and $M_{y\_load\_RF}$ are the torque loads on the left and right front wheel due to the tire forces/moments and brake torque, respectively. For example $M_{y\_load\_LF}$ is expressed by:

$$M_{y\_load\_LF} = -F_{xLF} \times (hwc + Z_{LF}) + M_{yresisLF} + M_{ybkF} \tag{67}$$

where F_{xLF} is tire longitudinal force, $hwc + Z_{LF}$ is the deflected tire radius, $M_{yresisLF}$ is the tire resistance of moment and M_{ybkF} is brake torque.

The angular acceleration of driveshaft is the average of left and right wheel acceleration such as:

$$\dot{\omega}_g = 0.5N_{diff\_F} \times (\dot{\omega}_{whLF} + \dot{\omega}_{whRF}) \tag{68}$$

Substitute equation 68for 66, the left and right wheel acceleration is:

$$\begin{aligned}
\dot{\omega}_{whLF} &= \frac{0.5T_g \cdot N_{diff_F} + M_{y_load_LF} + \dfrac{I_{trans_drv_F} \cdot N_{diff_F}{}^2 \left(M_{y_load_LF} - M_{y_load_RF}\right)}{4 \cdot \left(I_{wF} + I_{axle_RF}\right)}}{I_{wF} + I_{axle_LF} + \dfrac{1}{4} \cdot I_{trans_drv_F} \cdot N_{diff_F}{}^2 \left(1 + \dfrac{I_{wF} + I_{axle_LF}}{I_{wF} + I_{axle_RF}}\right)} \\
\dot{\omega}_{whRF} &= \frac{0.5T_g \cdot N_{diff_F} + M_{y_load_RF} + \dfrac{I_{trans_drv_F} \cdot N_{diff_F}{}^2 \left(M_{y_load_RF} - M_{y_load_LF}\right)}{4 \cdot \left(I_{wF} + I_{axle_LF}\right)}}{I_{wF} + I_{axle_RF} + \dfrac{1}{4} \cdot I_{trans_drv_F} \cdot N_{diff_F}{}^2 \left(1 + \dfrac{I_{wF} + I_{axle_RF}}{I_{wF} + I_{axle_LF}}\right)}
\end{aligned} \tag{69}$$

Equation 69 is for the case of the open front differential. The following equations are used for all kinds of differential systems for four wheels:

$$
\begin{aligned}
\dot{\omega}_{whLF} &= \frac{M_{y\_LF} + M_{y\_load\_LF} + \dfrac{I_{trans\_drv\_F} \cdot N_{diff\_F}{}^2 \left(M_{y\_load\_LF} - M_{y\_load\_RF}\right)}{4 \cdot \left(I_{wF} + I_{axle\_RF}\right)}}{I_{wF} + I_{axle\_LF} + \dfrac{1}{4} \cdot I_{trans\_drv\_F} \cdot N_{diff\_F}{}^2 \left(1 + \dfrac{I_{wF} + I_{axle\_LF}}{I_{wF} + I_{axle\_RF}}\right)} \\
\dot{\omega}_{whRF} &= \frac{M_{y\_RF} + M_{y\_load\_RF} + \dfrac{I_{trans\_drv\_F} \cdot N_{diff\_F}{}^2 \left(M_{y\_load\_RF} - M_{y\_load\_LF}\right)}{4 \cdot \left(I_{wF} + I_{axle\_LF}\right)}}{I_{wF} + I_{axle\_RF} + \dfrac{1}{4} \cdot I_{trans\_drv\_F} \cdot N_{diff\_F}{}^2 \left(1 + \dfrac{I_{wF} + I_{axle\_RF}}{I_{wF} + I_{axle\_LF}}\right)} \\
\dot{\omega}_{whLR} &= \frac{M_{y\_LR} + M_{y\_load\_LR} + \dfrac{I_{trans\_drv\_R} \cdot N_{diff\_R}{}^2 \left(M_{y\_load\_LR} - M_{y\_load\_RR}\right)}{4 \cdot \left(I_{wR} + I_{axle\_RR}\right)}}{I_{wR} + I_{axle\_LR} + \dfrac{1}{4} \cdot I_{trans\_drv\_R} \cdot N_{diff\_R}{}^2 \left(1 + \dfrac{I_{wR} + I_{axle\_LR}}{I_{wR} + I_{axle\_RR}}\right)} \\
\dot{\omega}_{whRR} &= \frac{M_{y\_RR} + M_{y\_load\_RR} + \dfrac{I_{trans\_drv\_R} \cdot N_{diff\_R}{}^2 \left(M_{y\_load\_RR} - M_{y\_load\_LR}\right)}{4 \cdot \left(I_{wR} + I_{axle\_LR}\right)}}{I_{wR} + I_{axle\_RR} + \dfrac{1}{4} \cdot I_{trans\_drv\_R} \cdot N_{diff\_R}{}^2 \left(1 + \dfrac{I_{wR} + I_{axle\_RR}}{I_{wR} + I_{axle\_LR}}\right)}
\end{aligned}
\tag{70}
$$

References

1. Gurm, J. S., Chen, W. J., Keyvanmanesh, A. and Abe, T, “Transient Clunk Response of a Driveline System: Laboratory Experiment and Analytical Studies”, SAE International, 2007-01-2233, 2007.
2. Peter Wright, “*Formula1 Technology*”, The Society of Automotive Engineers, Warrendale, PA, 2001.

Appendix

Figure 48 shows the torques acting on both sides of a locked clutch.

M_{g1} and M_{g2} are the torque acting on each side of the shaft. If this is the clutch between the engine and transmission, M_{g1} is the engine torque applied on the crankshaft while M_{g2} is the torque load from the transmission. On the other hand, if this is the clutch between left and right wheels (differential clutch), they are the torque load on the wheels due to the tire forces/moment and brake torques.

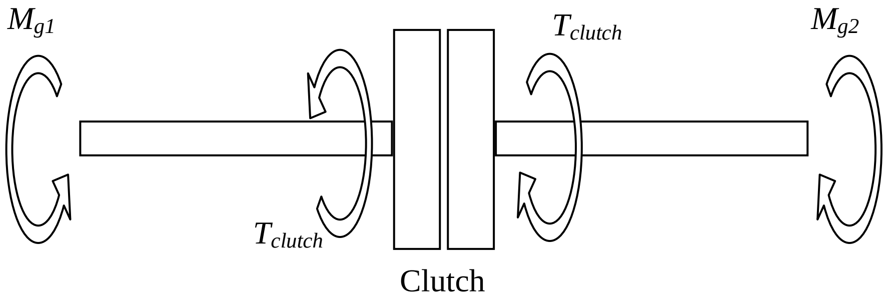

Figure 48. Torques acting on both sides of a locked clutch.

The angular speed on each side is described by:

$$\begin{aligned} M_{g1} - T_{clutch} &= I_{axle\_1} \cdot \dot{\omega}_{g1} \\ M_{g2} + T_{clutch} &= I_{axle\_2} \cdot \dot{\omega}_{g2} \end{aligned} \tag{71}$$

If the clutch is locked, the angular acceleration of both sides are synchronized such as:

$$\dot{\omega}_{g1} = \dot{\omega}_{g2} \tag{72}$$

From equations 71 and 72,

$$M_{g2} + T_{clutch} = I_{axle\_2} \cdot \left(\frac{M_{g1} - T_{clutch}}{I_{axle\_1}} \right) \tag{73}$$

From equation 73, the torque loaded on the clutch when it is locked is:

$$T_{clutch\_lock} = \frac{M_{g1} - M_{g2} \cdot \frac{I_{axle\_1}}{I_{axle\_2}}}{1 + \frac{I_{axle\_1}}{I_{axle\_2}}} \tag{74}$$

Therefore, if the torque load derived from equation 74 is smaller than the torque capacity of the clutch, the clutch can be considered as locked. On the other hand, if the torque load exceeds the torque capacity, the clutch can be considered as slipping.

Notation

$D_{driveline}$ — Torsional damping coefficient of driveline

D_{Lock_F} — Torsional damping coefficient of front locked differential

D_{Lock_R} — Torsional damping coefficient of rear locked differential

D_{Lock_TC} — Torsional damping coefficient of locked drive shaft of part-time 4WD

$d\omega_{clutch}$ — Differential of angular speeds between input and output plate of mechanical clutch

$d\omega_{clutch\_old}$ — Differential of angular speeds between input and output plate of mechanical clutch (at 1 calculation time step before)

$d\omega_{clutch\_trcase}$ — Differential of angular speeds between front and rear driveshaft

$d\omega_{clutch\_trcase\_old}$ — Differential of angular speeds between front and rear driveshaft (at 1 calculation time step before)

$d\omega_{clutch\_diff}$ — Differential of angular speeds between left and right wheels

$d\omega_{clutch\_diff\_old}$ — Differential of angular speeds between left and right wheels (at 1 calculation time step before)

E_{diff_F} — Efficiency of front differential (driving)

$E_{diff\_F\_rev}$ — Efficiency of front differential (coasting)

E_{diff_R} — Efficiency of rear differential (driving)

$E_{diff\_R\_rev}$ — Efficiency of rear differential (coasting)

ESC_state — ESC engine torque control state

E_{trcase} — Efficiency of transfer case (driving)

E_{trcase_rev} — Efficiency of transfer case (coasting)

E_{trans} — Efficiency of transmission (driving)

E_{trans_rev} — Efficiency of transmission (coasting)

F_{xLF} — Longitudinal force of left-front tire

F_{xRF} — Longitudinal force of right-front tire

F_{xLR} — Longitudinal force of left-rear tire

F_{xRR} — Longitudinal force of right-rear tire

F_{cvt_gear} — CVT gear ratio, function of a throttle position and transmission output speed

$F_{cvt\_efficiency}$ — CVT efficiency (driving), function of a transmission gear ratio

$F_{cvt\_efficiency\_rev}$ — CVT efficiency (coasting), function of a transmission gear ratio

f_{et} — Engine torque, function of a throttle position and crank shaft rotational speed

f_{dsh} — Shift down timing (transmission output rotational speed and throttle position)

f_{giet} — Inertia of transmission, function of the selected gear

f_{gr} — Transmission gear ratio, function of the selected gear

f_{lsd} — Torque difference, function of speed difference of the differential

f_{tki} — Torque capacity, function of the speed ratio of torque converter

f_{tr} — Torque ratio, function of speed ratio of torque converter

f_{trcase} — Torque difference, function of speed difference of ransfer case

f_{ush} — Shift up timing (transmission output rotational speed and throttle position)

G_{P_ESC} — P gain of ECS/TCS engine torque controller

G_{I_ESC} — I gain of ECS/TCS engine torque controller

hwc — Unloaded wheel radius

$I_{cvt\_input\_pulley}$ — Moment of inertia of the CVT input pulley

$I_{cvt\_output\_pulley}$ — Moment of inertia of the CVT output pulley

$I_{driveline}$ — Total moment of inertia of driveline, presented at after the transmission gearbox.

$I_{driveline\_front\_end}$ — Half (engine side) of the total moment of inertia of driveline, presented at after the transmission gearbox.

$I_{driveline\_rear\_end}$ — Half (wheel side) of the total moment of inertia of driveline, presented at after the transmission gearbox.

I_e — Moment of inertia of Engine (all rotating parts)

I_{tc_in} — Moment of inertia of half of the engine side of the torque transfer device

I_{tc_out} — Moment of inertia of half of the transmission side of the torque transfer device

I_{trans} — Moment of inertia of all the rotating parts with the transmission. The inertial is represented just after the gearbox.

$I_{trans\_drv\_F}$ — Front driveshaft inertia with a half portion of the transmission inertia. The inertia is represented just before the differential gearbox.

$I_{trans\_drv\_R}$ — Rear driveshaft inertia with a half portion of the transmission inertia. The inertia is represented just before the differential gearbox.

I_{shaft_F} — Moment of inertia of front drive shaft

I_{shaft_R} — Moment of inertia of rear drive shaft

I_{axle_F} — Total moment of inertia from the front driveshaft to wheels, represented after the transfer case.

I_{axle_R} — Total moment of inertia from the rear driveshaft to wheels, represented after the transfer case.

I_{axle_LF} — Moment of inertia of a left half of the front axle

I_{axle_RF} — Moment of inertia of a right half of the rear axle

I_{axle_LR} — Moment of inertia of a left half of the front axle

I_{axle_RR} — Moment of inertia of a right half of the rear axle

I_{wF} — Moment of inertia of a front wheel

I_{wR} — Moment of inertia of a rear wheel

$K_{driveline}$ — Torsional stiffness of driveline

K_{Lock_F} — Torsional stiffness of the front locked differential

K_{Lock_R} — Torsional stiffness of the rear locked differential

K_{Lock_TC} — Torsional stiffness of the central locked transfer case

M_{ybkF} — Braking torque of a front wheel

M_{ybkR} — Braking torque of a rear wheel

M_{y_LF} — Drive torque of the left front wheel

M_{y_RF} — Drive torque of the right front wheel

M_{y_LR} — Drive torque of the left rear wheel

M_{y_RR} — Drive torque of the right rear wheel

$M_{y\_load\_LF}$ — Torque load on the left front wheel due to the tire force/moment and brake torque

$M_{y\_load\_RF}$ — Torque load on the right front wheel due to the tire force/moment and brake torque

$M_{y\_load\_LR}$ — Torque load on the left rear wheel due to the tire force/moment and brake torque

$M_{y\_load\_RR}$ — Torque load on the right rear wheel due to the tire force/moment and brake torque

$M_{yresisLF}$ — Rolling resistant torque of the left front wheel

$M_{yresisRF}$ — Rolling resistant torque of the right front wheel

$M_{yresisLR}$ — Rolling resistant torque of the left rear wheel

$M_{yresisRR}$ — Rolling resistant torque of the right rear wheel

N_{diff_F} — Gear ratio of the front differential

N_{diff_R} — Gear ratio of the rear differential

N_{trans} — Gear ratio of the transmission

N_{trans_inst} — Instant gear ratio of the CVT (without dynamic time delay)

N_{trcase} — Gear ratio of the transfer case

S_{tc} — Speed ration of the torque converter

$T_{bias\_to\_rear}$ — Torque bias to the rear wheels (Full-Time 4WD)

T_{c_cvt} — Dynamic time constant of CVT

T_e — Engine torque

$T_{e\_control}$ — Engine torque modulated by ESC/TCS

$T_{e\_DRV\_rq}$ — Driver requesting engine torque

$T_{e\_ESC\_rq}$ — Engine torque requested by ESC/TCS

T_{e_target} — ESC targeting engine torque

T_{clutch_cap} — Maximum torque capacity of main clutch

T_{clutch_lock} — Torque load on the locked main clutch.

$T_{clutch\_trcase\_cap}$ — Maximum torque capacity of transfer case clutch

$T_{clutch\_trcase\_lock}$ — Torque load on the locked transfer case clutch.

$T_{clutch\_diff\_cap}$ — Maximum torque capacity of differential clutch

$T_{clutch\_diff\_lock}$ — Torque load on the locked differential clutch.

T_g — Transmission output torque

T_{gF} — Torque at front drive shaft

T_{gR} — Torque at rear drive shaft

T_{grout} — Transmission gearbox output torque

T_{lock_F} — Torque due to torsion of front axle

T_{lock_R} — Torque due to torsion of rear axle

T_{lock_trcase} — Torque due to torsion of front and back drive shafts

T_{tcin} — Input torque of the torque transfer device (used for internal calculation)

T_{tcin}^{*} — Input torque of the torque transfer device (compensated by the engine inertial term when the clutch is locked: used for output plot)

T_{tcout} — Output torque of the torque transfer device (used for internal calculation)

T_{tcout}^{*} — Output torque of the torque transfer device (compensated by the engine inertial term when the clutch is locked: used for output plot and criteria of driving/coasting efficiencies)

$throttle$ — Throttle position, normalized to have a range of 0 to 1

α_e — Engine angular acceleration

α_{grout} — Transmission gearbox output angular acceleration

Z_{LF} — Tire deformation of left front

Z_{RF} — Tire deformation of right front

Z_{LR} — Tire deformation of left rear

Z_{RR} — Tire deformation of right rear

ϕ_e — Engine rotation angle

ϕ_g — Transmission output shaft rotation angle

ϕ_{gF} — Front drive shaft rotation angle

ϕ_{gR} — Rear drive shaft rotation angle

ϕ_{grout} — Transmission gearbox output rotation angle

ϕ_{tco} — Torque transfer device output angle

ϕ_{whLF} — Left front wheel rotation angle

ϕ_{whRF} — Right front wheel rotation angle

ϕ_{whLR} — Left rear wheel rotation angle

ϕ_{whRR} — Right rear wheel rotation angle

ω_e — Engine angular speed

ω_g — Transmission output angular speed

ω_{gF} — Front drive shaft angular speed

ω_{gR} — Rear drive shaft angular speed

ω_{grout} — Transmission gearbox output angular speed

ω_{tco} — Torque transfer device output angular speed

$\omega_{n\_driveline}$ — Natural frequency of driveline

ω_{whLF} — Left front wheel angular speed

ω_{whRF} — Right front wheel angular speed

ω_{whLR} — Left rear wheel angular speed

ω_{whRR} — Right rear wheel angular speed

$\zeta_{driveline}$ — Damping ratio of driveline