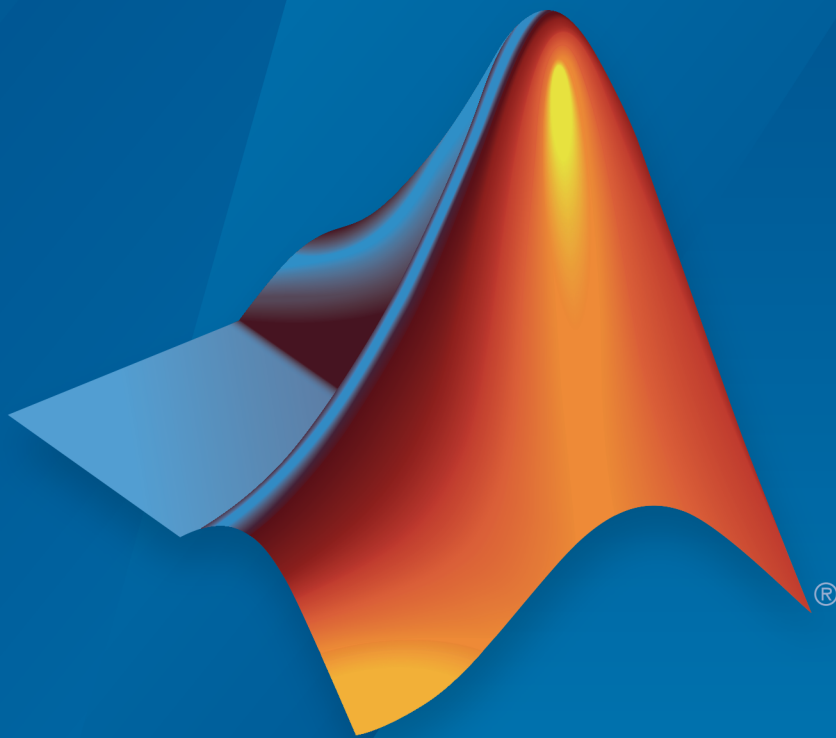


Simscape™ Driveline™

User's Guide



MATLAB® & SIMULINK®

R2016a



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*Simscape™ Driveline™ User's Guide*

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## Getting Started

<b>1</b>	<b>Introducing Simscape Driveline Software</b>	
	<b>Simscape Driveline Product Description</b> . . . . .	<b>1-2</b>
	Key Features . . . . .	<b>1-2</b>
	<b>Related Products</b> . . . . .	<b>1-3</b>
	Required Products . . . . .	<b>1-3</b>
	Other Related Products . . . . .	<b>1-3</b>
	<b>Drivetrain Model</b> . . . . .	<b>1-5</b>
	What the Model Represents . . . . .	<b>1-5</b>
	What the Model Illustrates . . . . .	<b>1-5</b>
	Open CR-CR Transmission Example Model . . . . .	<b>1-7</b>
	Run the Model . . . . .	<b>1-9</b>
	Modify the Model . . . . .	<b>1-13</b>
	<b>What You Can Do with Simscape Driveline Software</b> .	<b>1-17</b>
	What Simscape Driveline Software Contains . . . . .	<b>1-17</b>
	Model Driveline Systems . . . . .	<b>1-18</b>
	Model Inertias and Gears . . . . .	<b>1-19</b>
	Model Dynamic Driveline Elements . . . . .	<b>1-20</b>
	Model Custom Driveline Elements . . . . .	<b>1-20</b>
	Actuate and Sense Motion . . . . .	<b>1-20</b>
	Simulate and Analyze Motion . . . . .	<b>1-21</b>

<b>Start a New Simscape Driveline Model</b> .....	<b>2-2</b>
<b>Build a Driveline Model</b> .....	<b>2-3</b>
<b>Basic Motion, Torque, and Force Modeling</b> .....	<b>2-6</b>
About Inertia, Motion, and Gears .....	<b>2-6</b>
Couple Rotational Motion with Gears .....	<b>2-6</b>
Couple Two Spinning Inertias with Simple Gear .....	<b>2-7</b>
Couple Two Spinning Inertias with Variable Ratio Transmission .....	<b>2-13</b>
Couple Three Spinning Inertias with Planetary Gear .	<b>2-15</b>
<b>Driveline Actuation</b> .....	<b>2-20</b>
About Torques, Forces, and Motion .....	<b>2-20</b>
Actuate a Driveline with Torques and Forces .....	<b>2-21</b>
Actuate a Driveline with Motions .....	<b>2-21</b>
Set Initial Conditions of Driveline Motion .....	<b>2-22</b>
<b>Gear Coupling Control with Clutches</b> .....	<b>2-23</b>
About Motion, Gears, and Clutches .....	<b>2-23</b>
Engage and Disengage Gears with Clutches .....	<b>2-23</b>
Brake Motion with Clutches .....	<b>2-28</b>
Model Friction Clutches at a Fundamental Level .....	<b>2-30</b>
<b>Gears, Clutches, and Transmissions</b> .....	<b>2-31</b>
About Gears, Clutches, and Transmissions .....	<b>2-31</b>
Model a Two-Speed Transmission with Braking .....	<b>2-32</b>
Model a CR-CR 4-Speed Transmission Driveline with Braking .....	<b>2-38</b>
<b>Complete Vehicle Model</b> .....	<b>2-43</b>
About the Complete Vehicle Model .....	<b>2-43</b>
Model the Engine .....	<b>2-44</b>
Model the Transmission .....	<b>2-46</b>
Couple the Engine to the Transmission .....	<b>2-46</b>
Model the Wheels, Tires, and Road .....	<b>2-47</b>
Control the Clutches .....	<b>2-49</b>
Run the Model .....	<b>2-52</b>

<b>Specialized and Customized Driveline Components</b> . . . . .	3-2
Optimal Physical Modeling in the Simscape Environment . . .	3-2
Reasons for Specialized Driveline Components . . . . .	3-2
Greater Model Fidelity and Performance . . . . .	3-3
<b>Effective Inertias and Driveshafts</b> . . . . .	3-4
Model a Variable Inertia . . . . .	3-4
Model Driveshafts with Loss . . . . .	3-6
<b>Specialized Gears</b> . . . . .	3-7
Custom Planetary Gear Model . . . . .	3-7
Model Gears with Losses . . . . .	3-8
Constant and Load-Dependent Gear Efficiencies . . . . .	3-9
<b>Specialized Clutches</b> . . . . .	3-11
Clutches, Clutch-Like Elements, and Coulomb Friction . . . .	3-11
Model Clutches with Viscous Friction Loss . . . . .	3-12
Model Realistic Clutch Pressure Signals . . . . .	3-16
Automatic Transmission with a Dual Clutch . . . . .	3-16
<b>Rotational-Translational Couplings</b> . . . . .	3-19
Convert Between Rotational and Translation Motion . . . . .	3-19
Use Simscape and Simscape Driveline Elements to Couple Rotation and Translation . . . . .	3-19
<b>Modeling Transmissions</b> . . . . .	3-21
Transmission Templates . . . . .	3-21
Transmission Ports . . . . .	3-21
Gear Input Signal . . . . .	3-21
Initial States . . . . .	3-22
Clutch Control . . . . .	3-23
Inertias and Friction Losses . . . . .	3-23
Real-Time Simulation . . . . .	3-24
<b>CR-CR 4-Speed Transmission</b> . . . . .	3-25
Transmission Overview . . . . .	3-25
Clutch Schedule . . . . .	3-25
Power Flow . . . . .	3-26
Drive Ratio . . . . .	3-27

<b>Lepelletier 6-Speed Transmission</b> .....	<b>3-29</b>
Transmission Overview .....	3-29
Clutch Schedule .....	3-29
Power Flow .....	3-30
Drive Ratio .....	3-31
<b>Lepelletier 7-Speed Transmission</b> .....	<b>3-34</b>
Transmission Overview .....	3-34
Clutch Schedule .....	3-34
Power Flow .....	3-35
Drive Ratio .....	3-36
<b>Ravigneaux 4-Speed Transmission</b> .....	<b>3-39</b>
Transmission Overview .....	3-39
Clutch Schedule .....	3-39
Power Flow .....	3-40
Drive Ratio .....	3-41
<b>8-Speed Transmission</b> .....	<b>3-43</b>
Transmission Overview .....	3-43
Clutch Schedule .....	3-43
Power Flow .....	3-44
Drive Ratio .....	3-46
<b>9-Speed Transmission</b> .....	<b>3-47</b>
Transmission Overview .....	3-47
Clutch Schedule .....	3-47
Power Flow .....	3-48

## Analyzing Driveline Models and Simulations

# 4

<b>Driveline Simulation Performance</b> .....	<b>4-2</b>
About Simulation Performance .....	4-2
Adjust Model Fidelity .....	4-2
Optimize Simulation of Stiff Drivelines .....	4-3
Optimize Simulation of Clutches .....	4-4
<b>Driveline Simulation Errors</b> .....	<b>4-7</b>
Fix Driveline Modeling and Simulation Errors .....	4-7



Correct Overconstrained and Conflicting Degrees of Freedom	4-7
Correct Clutch and Transmission Errors	4-8
Correct Inconsistent Initial Conditions	4-8
<b>Driveline Degrees of Freedom</b>	<b>4-10</b>
About Driveline Degrees of Freedom and Constraints	4-10
Identify Degrees of Freedom	4-11
Define Fundamental Degrees of Freedom	4-11
Define Connected Degrees of Freedom	4-13
Define Constrained Degrees of Freedom	4-14
Actuate, Sense, and Terminate Degrees of Freedom	4-18
Count Independent Degrees of Freedom	4-19
Count Degrees of Freedom in a Simple Driveline with a Clutch	4-20
<b>Driveline States — Effect of Clutches</b>	<b>4-24</b>
Driveline States and Degrees of Freedom	4-24
Find and Use Driveline States	4-25
<b>How Simscape Driveline Simulates a Driveline System</b>	<b>4-27</b>
About Simscape Driveline and Simscape Simulation	4-27
Clutch State Determination	4-27
<b>Simscape Driveline Limitations</b>	<b>4-28</b>
Simscape Driveline and Simulink Limitations	4-28
Additional Simscape Driveline Limitations	4-28



# Getting Started



# Introducing Simscape Driveline Software

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- “Simscape Driveline Product Description” on page 1-2
- “Related Products” on page 1-3
- “Drivetrain Model” on page 1-5
- “What You Can Do with Simscape Driveline Software” on page 1-17

## Simscape Driveline Product Description

### Model and simulate rotational and translational mechanical systems

Simscape™ Driveline™ provides component libraries for modeling and simulating rotational and translational mechanical systems. It includes models of worm gears, lead screws, and vehicle components such as engines, tires, transmissions, and torque converters. You can use these components to model the transmission of mechanical power in helicopter drivetrains, industrial machinery, automotive powertrains, and other applications. You can integrate electrical, hydraulic, pneumatic, and other physical systems into your model using components from the Simscape family of products.

Simscape Driveline helps you develop control systems and test system-level performance. You can create custom component models with the MATLAB® based Simscape language, which enables text-based authoring of physical modeling components, domains, and libraries. You can parameterize your models using MATLAB variables and expressions, and design control systems for your physical system in Simulink®. To deploy your models to other simulation environments, including hardware-in-the-loop (HIL) systems, Simscape Driveline supports C-code generation.

### Key Features

- Gear models, including planetary, differential, and worm gears with meshing losses, viscous losses, and thermal effects
- Clutch models, including cone, disk friction, synchronizer, unidirectional, and dog clutch
- Vehicle component models, including engine, tire, torque converter, and vehicle dynamics
- Models of translational elements, including leadscrew, rack and pinion, and translational friction
- MATLAB based Simscape language for creating custom component models
- Physical units for parameters and variables, with all unit conversions handled automatically
- Support for C-code generation (with Simulink Coder™)

## Related Products

In this section...
“Required Products” on page 1-3
“Other Related Products” on page 1-3

### Required Products

To use the Simscape Driveline product, you must have installed current versions of the following products:

- MATLAB
- Simulink
- Simscape

### Other Related Products

On the MathWorks Web site, on the Simscape Driveline product page, the related products that are listed include toolboxes and blocksets that extend the capabilities of MATLAB and Simulink. These products can enhance Simscape Driveline modeling and simulation in various applications.

#### Physical Modeling Product Family

Use the Physical Modeling product family to model physical systems in Simulink. In addition to Simscape Driveline software, the product family includes:

- Simscape, the platform and unifying environment for Physical Modeling products.
- Simscape Electronics™, for modeling and simulating electronic systems.
- Simscape Fluids™, for modeling and simulating hydromechanical systems.
- Simscape Multibody™, for modeling and simulating mechanical systems.
- Simscape Power Systems™, for modeling and simulating electrical power systems.

## **For Information About MathWorks Products**

- If you have the product installed, see the online documentation for that product.
- See the “Products” section at the MathWorks Web site at [www.mathworks.com](http://www.mathworks.com).



# Drivetrain Model

## In this section...

“What the Model Represents” on page 1-5

“What the Model Illustrates” on page 1-5

“Open CR-CR Transmission Example Model” on page 1-7

“Run the Model” on page 1-9

“Modify the Model” on page 1-13

## What the Model Represents

The model `sdl_crcr` simulates a complete drivetrain. This example helps you understand how to model driveline components with Simscape Driveline blocks, connect them into a realistic model, use Simulink blocks and variant subsystems in driveline modeling, and simulate and modify a drivetrain model.

This driveline mechanism is part of a full vehicle, without the engine or engine-drivetrain coupling, and without the final differential and wheel assembly. The model includes an actuating torque, driver and driven shafts, a four-speed transmission, and a braking clutch.

For a complete vehicle model that uses this drivetrain, see the `sdl_vehicle` example model and “Complete Vehicle Model” on page 2-43.

## What the Model Illustrates

The `sdl_crcr` model contains a driveline that accepts a driving torque. The driveline system transfers this torque and the associated angular motion from the input or drive shaft to an output or driven shaft through a transmission. The model includes a CR-CR (carrier-ring-carrier-ring) four-speed transmission subsystem, based on two gears and four clutches. (The example does not use the reverse gear in the CR-CR transmission.) You can set the transmission to four different gear combinations, allowing four different effective torque and angular velocity ratios. A fifth clutch, outside the transmission, acts as a brake on the driven shaft.

The CR-CR 4-Speed transmission subsystem illustrates a critical feature of transmission design, the *clutch schedule*. To be fully engaged, the transmission, with four clutches and

two planetary gears, requires two clutches to be locked and the other two unlocked at any time. (The transmission reverse clutch is not applicable here.) The choice of which two clutches to lock determines the effective gear ratio across the transmission. The clutch schedule is the table of locked and free clutches corresponding to different gear settings. If all four clutches are unlocked, the transmission is in neutral. If the clutches are completely disengaged, no torque or motion at all is transferred across the transmission.

### Clutch Schedule for the CR-CR 4-Speed Transmission

Gear Setting	Clutch A State	Clutch B State	Clutch C State	Clutch D State	Clutch R State	Drive Ratio
1	<i>L</i>	F	F	<i>L</i>	F	$1 + g_o$
2	<i>L</i>	F	<i>L</i>	F	F	$1 + g_o/(1 + g_i)$
3	<i>L</i>	<i>L</i>	F	F	F	1
4	F	<i>L</i>	<i>L</i>	F	F	$g_i/(1 + g_i)$
Reverse	F	F	F	F	<i>L</i>	$-g_i$

- *L* = locked
- F = free
- $g_i$  = Input Planetary Gear ring-to-sun gear ratio
- $g_o$  = Output Planetary Gear ring-to-sun gear ratio

### Clutch Control Variant Subsystem

A **Variant Subsystem** block governs transmission gear changes. This block, named Clutch Control, contains two child subsystem blocks that provide different clutch control modes, or *variants*:

- Manual — Manually switch transmission clutches.
- Programmed — Automatically switch transmission clutches according to a programmed clutch schedule.

During simulation, one variant becomes active while the other does not. The choice of active variant determines which child subsystem controls the gear changes. By default, the Programmed variant is active and gear changes follow a programmed clutch

schedule. To manually switch gears during simulation, change the active variant to Manual.

## Open CR-CR Transmission Example Model

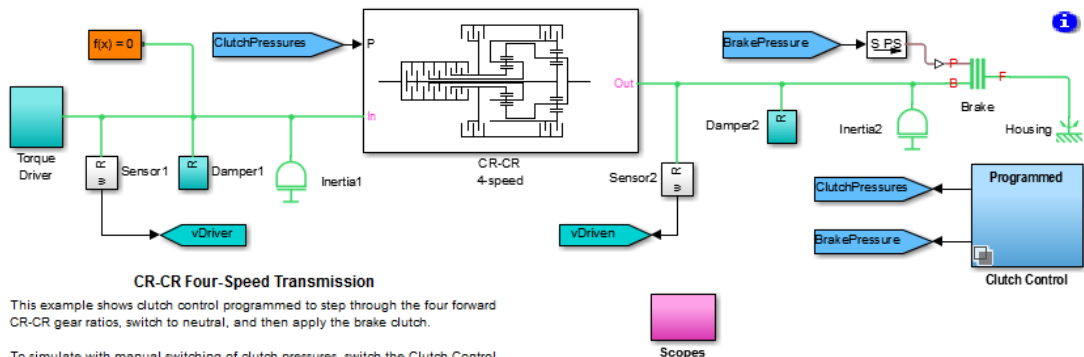
To get started quickly with the CR-CR transmission example model, do one of the following:

- At the MATLAB command line, enter `sdl_crcr`.
- If you are working in the MATLAB Help browser, click the model name `sdl_crcr` here.

### Block Diagram Model

Examine the model and its structure. The main model window contains the CR-CR transmission subsystem, the input or driver shaft assembly, and the output or driven shaft assembly. Each assembly consists of a driveline axis with applied damping and inertia torques. Each driveshaft balances the torques applied across its ends with the damping and inertia forces, thereby transmitting a net torque along the driveline.

The main model also includes a brake clutch. When this clutch is locked, the driven shaft stops turning. This clutch must remain unlocked if the CR-CR transmission is engaged.

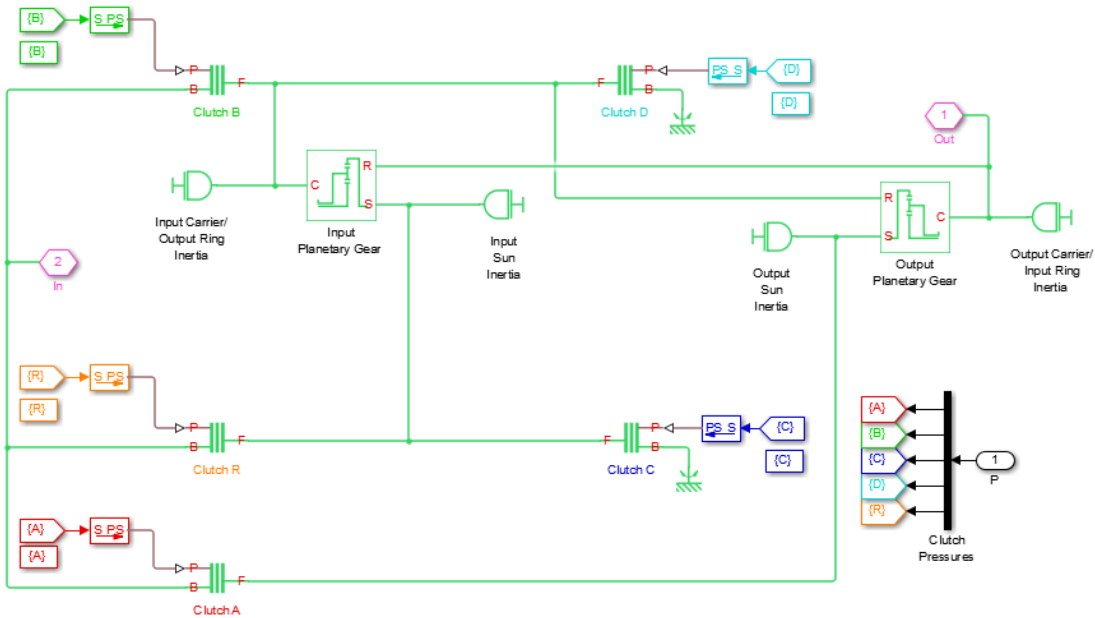


### Main Model Window

#### What the Model Contains—Opening the Subsystems

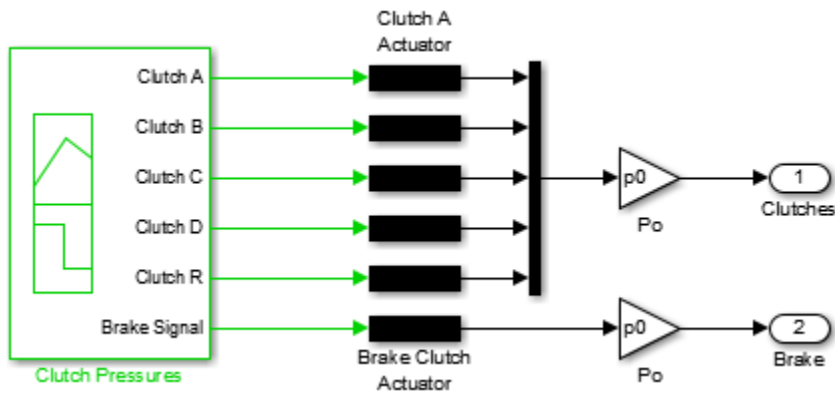
Open each subsystem.

The CR-CR 4-Speed transmission subsystem contains four clutches, two planetary gears, and four inertias (rotating bodies). Ignoring the reverse gear and its clutch, this transmission has four possible (forward) gear settings. Exactly two clutches must be locked at any one time for the transmission to engage and to avoid conflicting constraints on the gear motions.



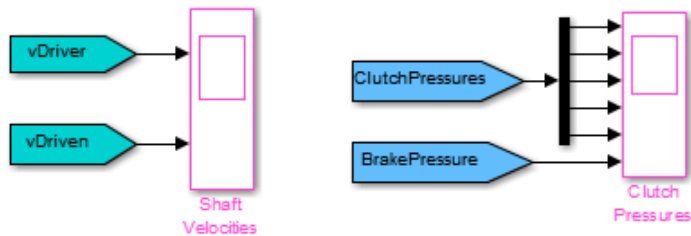
### CR-CR 4-Speed Transmission Subsystem

The Clutch Control variant subsystem provides the pressures that lock the necessary clutches. In its default state, the clutch controller is programmed to move the transmission through a fixed sequence of gears, then unlock all the transmission clutches. This control program allows the driven shaft to “coast” for a time, and then engage and lock the brake clutch to stop the driven shaft.



### Clutch Control Subsystem

The Scopes subsystem provides Scope blocks to display the clutch pressure and the driver and driven shaft velocity signals.



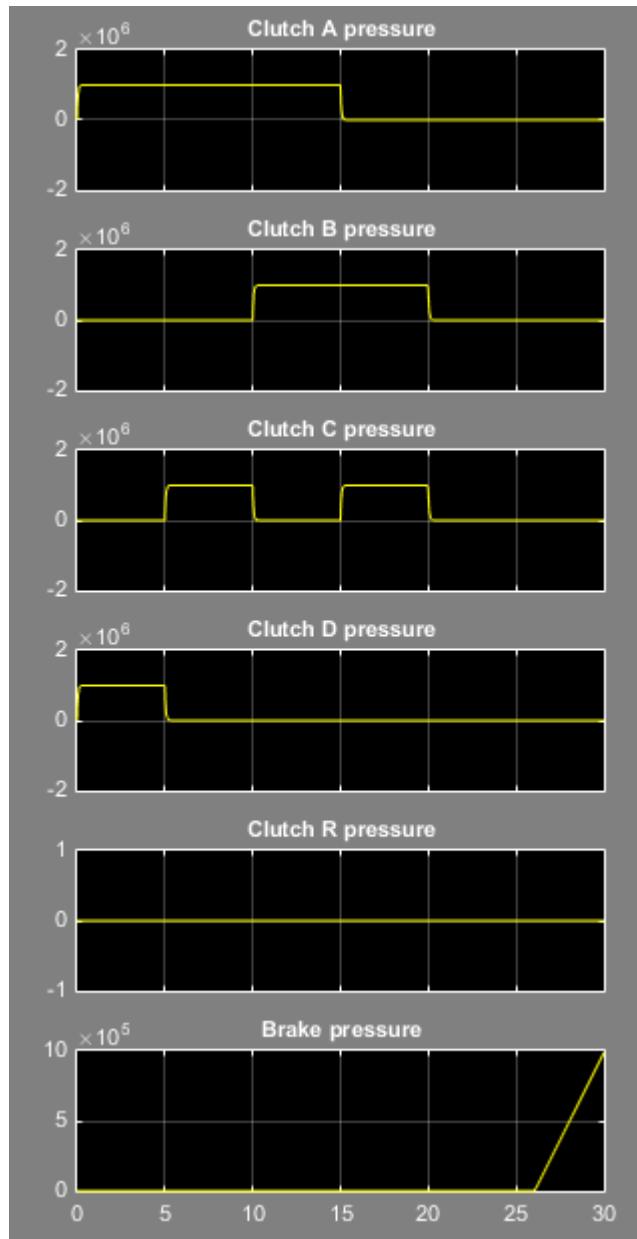
### Scopes Subsystem

### Run the Model

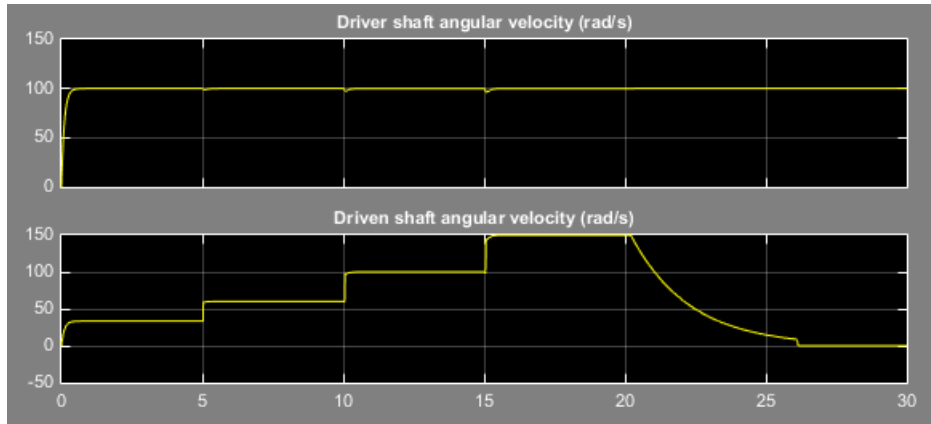
To display the CR-CR driveline model behavior:

- 1 Open the Scopes subsystem and then each of the Scope blocks. Close the Scopes subsystem.
- 2 Click **Start**. The model steps through the gears and then brakes.
- 3 Observe how the clutch pressure signals move the transmission into one gear after another, at 0, 5, 10, and 15 seconds of simulation time. Compare these clutch pressure signals to the clutch schedule in the CR-CR transmission subsystem to

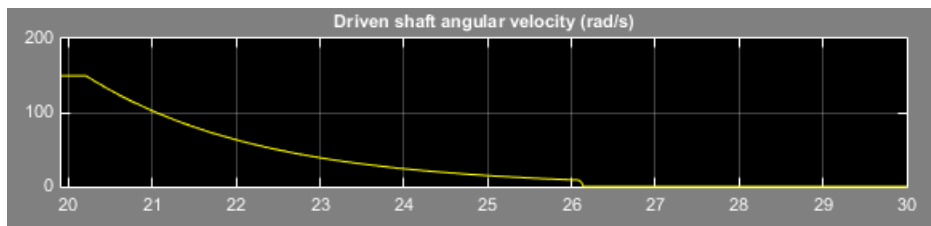
determine which gear settings the model is implementing. The model steps through gears 1, 2, 3, and 4, before coasting and then braking.



- 4 Compare the angular velocities of the driven and driver shafts. In the transmission, the two planetary gears are coupled in different ways in the different gear settings, producing different relationships between the driven and driver shaft velocities. The effective *drive ratio* of output to input shafts is the *reciprocal* of the ratio of output to input angular velocities.

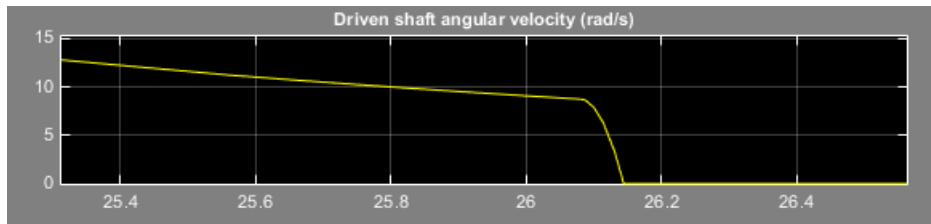


- 5 Observe what happens at 20 seconds. The transmission clutch pressures drop to zero, and the transmission disengages. The transmission ceases to transfer angular motion and torque from the driver to the driven shaft, and the driven shaft continues to spin from inertia alone. A small kinetic friction damping gradually slows the driven shaft over the next 6 seconds.



- 6 At 26 seconds of simulation time, the brake clutch pressure begins to rise from zero, and the brake clutch engages. The driven shaft decelerates more drastically now. Between 26.0 and 26.2 seconds, the brake clutch locks, and the driven shaft stops rotating completely.





## Modify the Model

You can modify this example model to explore other Simscape Driveline features. Here you modify and rerun the model to investigate two aspects of its motion.

- Measure the effective drive ratio of the CR-CR transmission in each gear setting that it steps through.
- Change the gear sequence.

### Measuring the Drive Ratio of the CR-CR Transmission States

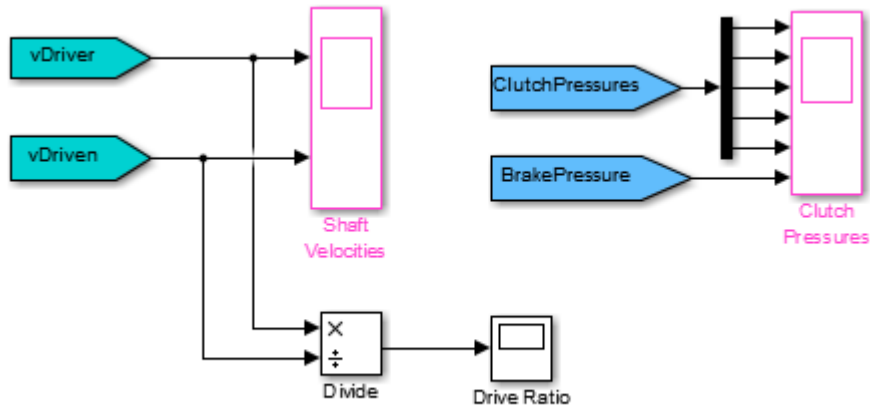
A transmission is a set of coupled gears. For a particular transmission gear setting, the ratio of driven (output) shaft velocity to the driver (input) is fixed. Its reciprocal, the *drive ratio*, is like a gear ratio of an individual gear coupling, but for the whole transmission.

Add and connect the necessary Simulink blocks to measure the drive ratio of the transmission.

- 1 Open the Scopes subsystem.
- 2 From the Simulink library, copy into the Scopes subsystem:
  - A Divide block from the Simulink Math Operations library.
  - A Scope block from the Simulink Sinks library.
- 3 From the  $v_{\text{Driver}}$  input signal, branch a signal line and connect it to the X input on the Divide block. From the  $v_{\text{Driven}}$  input signal, again branch a signal line. Connect it to the  $\div$  input on the Divide block.

The output-to-input drive ratio is the ratio of input to output velocities.

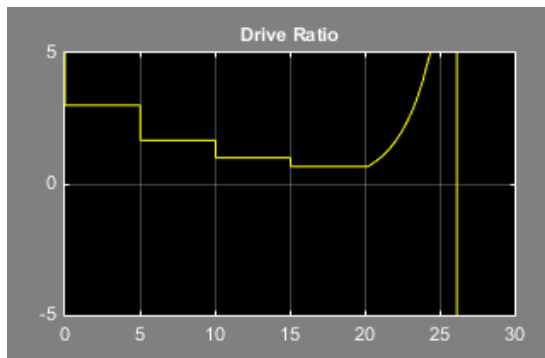
- 4 Connect the output of the Divide block to the Scope. Rename Scope to Drive Ratio.



### CR-CR 4-Speed Model with Drive Ratio Measurement

- 5 Open the Drive Ratio scope and restart the example. Observe how the drive ratio steps through a sequence of five-second states, in parallel with the clutch pressures and clutch modes, until it reaches 20 seconds. The drive ratio measurement after 20 seconds is not meaningful because the transmission is uncoupled.

Just after 26 seconds, the driven shaft velocity drops to zero, and the Divide block produces divide-by-zero warnings at the MATLAB command line.



- 6 Consult the table, Clutch Schedule for the CR-CR 4-Speed Transmission. Check the drive ratios for each gear, 1, 2, 3, and 4, in terms of the gear ratios of the two

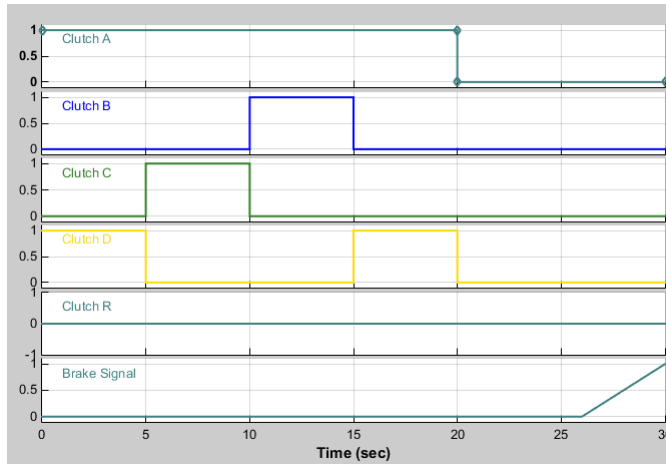
Planetary Gears in the transmission. Determine the numerical values for these drive ratios for gear settings 1, 2, 3, and 4. Then check them against the values displayed in the Drive Ratio scope.

The drive ratio sequence should be 3,  $5/3$ , 1, and  $2/3$ , respectively, for the first, second, third, and fourth intervals of five seconds each.

### **Changing the Transmission Gear Sequence**

When you first open the `sdl_crcr` example, the Clutch Control variant subsystem is programmed to step through CR-CR gear settings 1, 2, 3, and 4, before disengaging. Modify it to step through settings 1, 2, 3, and 1, then disengage. The fourth gear requires that A to be free, B to be locked, C to be locked, and D to be free. You have to modify the clutch pressure signal sequence from 15 to 20 seconds so that the transmission is set in first, not fourth, gear. The first gear requires clutches A and D to be locked and clutches B and C to be free.

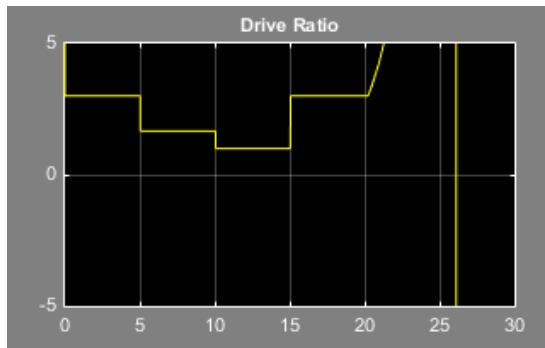
- 1** Determine the clutch states that correspond to first gear. Refer to table Clutch Schedule for the CR-CR 4-Speed Transmission.
- 2** Double-click Clutch Control.
- 3** In the Clutch Control subsystem, double-click Programmed.
- 4** In the Programmed subsystem, double-click Clutch Pressures. The signal builder window opens with the clutch pressure signals.
- 5** In the time interval 15–20 seconds, update clutch signals A-D to match first gear. Clutches A and D must lock, while clutches B and C must remain free. Specify a signal value of one to lock a clutch, zero to unlock it.



### Modified CR-CR 4-Speed Transmission Clutch Pressures

- 6 Run simulation.

Clutch pressures, clutch modes, and driven shaft velocities in the time interval 15–20 seconds now correspond to first gear. You can confirm this by referring to the Drive Ratio plot for the updated model. The ratio has changed from  $2/3$  (fourth gear) to 3 (first gear).



# What You Can Do with Simscape Driveline Software

## In this section...

“What Simscape Driveline Software Contains” on page 1-17

“Model Driveline Systems” on page 1-18

“Model Inertias and Gears” on page 1-19

“Model Dynamic Driveline Elements” on page 1-20

“Model Custom Driveline Elements” on page 1-20

“Actuate and Sense Motion” on page 1-20

“Simulate and Analyze Motion” on page 1-21

## What Simscape Driveline Software Contains

Simscape Driveline software is a set of block libraries in the Simulink environment and based on Simscape software. You connect Simscape Driveline blocks to normal Simulink blocks through Simscape physical signal blocks that define physical units.

The blocks in the Simscape Driveline library and the related mechanical blocks in the Simscape Foundation library are the elements to model driveline systems. These systems consist of one or more inertias and masses, rotating about or translating along one or more axes, constrained to rotate or translate together by gears, which transfer torque and forces to different parts of the driveline. You can represent drivelines with components organized into hierarchical subsystems, as in any Simulink model. You can:

- Constrain motion with gears
- Add complex dynamic elements such as clutches, clutch-like elements, and other couplings
- Represent such vehicle components as bodies and tires
- Actuate bodies with torques, forces, and motions
- Integrate the Newtonian rotational and translational dynamics, then measure the resulting motions

### Relation to Simscape Software


To model and simulate physical systems, Simscape Driveline models use such Simscape technologies as nondirectional physical connections and conserving ports, physical


signals carrying physical units, custom component modeling, specialized solvers, and data logging.

The Simscape mechanical rotational and translational domains form the basis of the Simscape Driveline block libraries and models. The Simscape Foundation library itself includes physical signal blocks; and basic mechanical blocks representing inertia, mass, and simple mechanical couplings. It also includes motion, torque, and force sources and sensors.

For more about modeling and simulating in the Simscape environment, see the “Simscape” documentation.

### **Physical Connections, Mechanical Conserving Ports, and Physical Signals**

On Simscape Driveline blocks, the mechanical conserving ports  anchor physical connection lines that, in this domain, represent mechanical axes. These axes are either rotation axes along which torque is transferred and around which inertias rotate, or translation axes along which force is transferred and along which masses translate.

Certain blocks defined in Simscape domains also require input or output signals that carry physical units, or physical signals. Simscape physical signal lines and ports  represent and connect physical signals with units. Conversion blocks allow you to convert dimensionless Simulink signals to Simscape physical signals, and back.

### **Model Driveline Systems**

Simscape Driveline software extends Simulink and Simscape software with blocks to model driveline components and properties, represent drivelines as physical networks, and to solve the equations of motion.

To build and run a Simscape Driveline model representation of a driveline:

- 1 Specify rotational inertia or translational mass for each body. Connect the bodies with physical connection lines representing driveline axes at mechanical conserving ports.  
  
If needed, ground the driveline to one or more mechanical references fixed in space.
- 2 Constrain the driveline axes to rotate or translate together by connecting them with gears. Gears impose static constraints on driveline motions and transfer torques and forces at fixed ratios.

- 3 As necessary, add dynamic elements that transfer torque, force, and motion among driveline axes in a nonstatic way. These elements include internal torque-generating components such as damped springs, clutches, clutch-like elements, transmissions, and torque converters. You can also construct and connect your own dynamic elements.

Similarly, add dynamic sources and environmental interactions, such as engines, vehicle bodies, and tires.

- 4 Set up mechanical sources and sensors to initiate and record body motions, as well as apply external torques and forces to the driveline.
- 5 Connect the Simscape Solver Configuration to the driveline, then configure it. Start the simulation, calling the Simulink and Simscape solvers to find the motions of the system. Display and analyze the motion.

## Model Inertias and Gears

Simscape Driveline software defines a driveline as a collection of rotating and translating bodies, defined by their rotational inertias and translational masses. Rotational and translational degrees of freedom (DoFs) originate on inertias and masses, but are carried by physical connection lines. Directly connecting one body to another constrains both bodies to rotate at the same angular or linear velocity. A torque or force applied to one body is applied to both. You can also ground driveline axes to mechanical references that do not move and that represent infinite effective inertia or mass.

---

**Note:** All Simscape Driveline DoFs are absolute in an implicit global coordinate system at rest, but are measured and used in a relative way, between one component and another. To measure with respect to the global rest frame, ground sensors or other components with mechanical reference blocks.

---

In a real driveline, the bodies can also be connected indirectly by gears that couple driveline axes. The gears constrain the axes to rotate together. These gears can be simple or complex and can couple two or more axes. The gears have two roles:

- Constraining the connected axes to rotate or translate together at velocities in fixed ratio or ratios.
- Transferring the torques or forces flowing along one or more axes to other axes, also in fixed ratio or ratios.

## Model Dynamic Driveline Elements

To create more realistic driveline models, you elaborate on simple drivelines consisting of inertias, masses, and gears. You add complex mechanical elements that generate torques and forces internally within the driveline, between one axis and another. Certain Simscape Driveline blocks encapsulate as subsystems entire models of complex driveline elements:

- Load-dependent loss models of nonideal gears
- Clutches and clutch-like elements that model the locking and unlocking of pairs of driveline axes by applying kinetic and static friction.
- Vehicle component models that represent engines, tires, and vehicle bodies
- Specialized torque and force models, such as torque converters, hard stops, and damped spring-like torsion

## Model Custom Driveline Elements

The blocks provided in the Simscape Foundation library can serve as starting points for developing variant or entirely new models to simulate the same components. You can also study masked subsystems by looking under their masks. If necessary, break such a block's library link before modifying it, and then create your own version. Or, create your own completely new blocks using Simscape Driveline and Simscape components, or with the Simscape language.

For more information on specialized driveline components, see “Specialized and Customized Driveline Components” on page 3-2.

## Actuate and Sense Motion

Simscape motion sources and sensors are the blocks that you use to insert and extract basic kinematic and dynamic information:

- Source blocks impart motion to driveline axes and impose externally defined torques and forces on the bodies of a driveline.
- Sensor blocks measure the motions of, and the torques and forces transferred along, the axes of a driveline system.

Source inputs and sensor outputs are physical signals that carry units.



## Simulate and Analyze Motion

Once you specify all the rotational inertias and translational masses of the bodies and interconnect the bodies with gears and other driveline elements, the dynamical problem of finding the system motion is solvable. To finish a driveline model and prepare it for simulation, you must connect the driveline to the Simscape solver. This solver defines certain aspects of the simulation and integrates the Newtonian dynamics for the system, applying all internal and external torques and constraints to find the motions of the bodies.

Once your model is ready for simulation, run it and analyze its motions, torques, and forces.

### Inverse Dynamics — Trimming and Linearization

In many cases, you do not know the torques and forces necessary to produce a given set of motions. By motion-actuating your driveline with motion sources and measuring the resulting torques and forces, you can find the torques and forces required to produce specified motions. This technique inverts the canonical approach to dynamics, which consists of finding motions from torques and forces.

A special case of inverse dynamics is *trimming*. This technique involves searching for steady-state motions of the bodies, when their accelerations and the torques and forces they experience vanish. Using the specialized tools in Simscape and Simulink, you can perturb such a steady motion state slightly to find how the system responds to small disturbances. The response indicates the system stability and suitability for controllers.

### Generating Code — Real-Time and Hardware-in-the-Loop Simulation

Simscape Driveline software is compatible with Simulink Acceleration modes, Simulink Coder, and Simulink Real-Time™ software. With these products, you can generate code versions of the models the you originally create in Simulink with block diagrams, enhancing simulation speed and model portability. A common application of generated code is defining real-time and hardware-in-the-loop simulations.

The presence of clutches in a driveline model induces locking-unlocking iterations and dynamical discontinuities. These discontinuities place certain restrictions on code generation. For more information about these restrictions, see “Driveline Simulation Performance” on page 4-2 and “Simscape Driveline Limitations” on page 4-28.



# Modeling Driveline Systems

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- “Start a New Simscape Driveline Model” on page 2-2
- “Build a Driveline Model” on page 2-3
- “Basic Motion, Torque, and Force Modeling” on page 2-6
- “Driveline Actuation” on page 2-20
- “Gear Coupling Control with Clutches” on page 2-23
- “Gears, Clutches, and Transmissions” on page 2-31
- “Complete Vehicle Model” on page 2-43

### Start a New Simscape Driveline Model

You can use the Simscape model template as a starting point for your Simscape Driveline models. The template provides the required `Solver Configuration` block and the commonly used `Simulink-PS Converter` and `PS-Simulink Converter` blocks.



To open the Simscape model template, at the MATLAB command prompt, enter `ssc_new`. Simscape software opens the model template along with the Foundation block library. Enter `sdl_lib` to open the Simscape Driveline block library.

## Build a Driveline Model



The example model in “Drivetrain Model” on page 1-5 illustrates a typical drivetrain system that you can model with Simscape Driveline software. It also illustrates the key rules for connecting driveline blocks to each other and the dual roles of Simscape physical connection lines in driveline modeling. Within the Simscape mechanical domain:

- The *across* variable is angular or linear velocity, depending on the type of mechanical ports you are connecting to, rotational or translational. Along any connection line, the velocity is the same.
- The *through* variable is torque or force, depending on the type of mechanical ports you are connecting to. Torques or forces are conserved along a connection line and always sum to zero at line branch points.

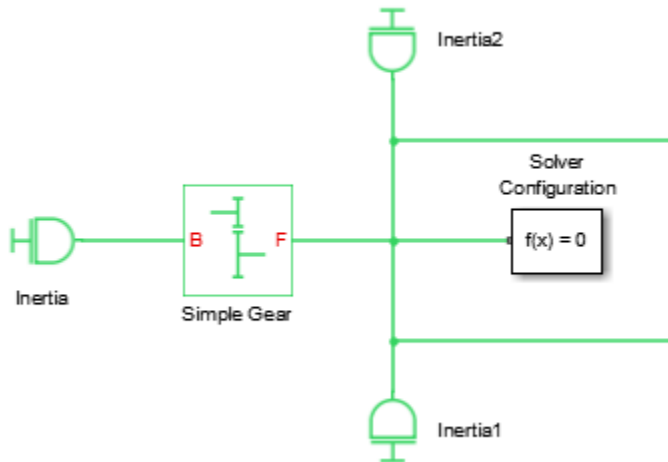
Before building and running the tutorial models, you should review these rules.

- Driveline blocks feature mechanical conserving ports  and, in some cases, physical signal ports  as well. You can connect mechanical ports only to other mechanical ports, and physical signal ports only to one another.

You cannot mix rotational and translational ports, or connect a mechanical conserving port to a physical signal port.

- The physical connection lines interconnecting mechanical ports  represent driveline axes and enforce physical relationships. Unlike physical signal and Simulink lines, they do not represent signals or mathematical operations, and they have no inherent directionality.
- A driveline connection line represents an idealized massless and perfectly rigid spinning shaft or translating axis. A driveline connection line between two ports constrains the two driveline components that are connected to the line to rotate or translate at the same velocity.
- You can branch mechanical connection lines. You must connect the end of any branch of a mechanical connection line to a mechanical port .
- Branching a driveline connection line modifies the physical constraints that it represents. All driveline components connected to the ends of a set of branched lines rotate or translate at the same velocity. For lines branched from a branch point, the sum of all torques or forces flowing in equals the sum of all torques or forces flowing out. How the torque or force is divided depends on the defining equations of the attached blocks in the rest of the system.

- Mechanical connection lines satisfying the velocity constraint must have the same initial velocities.



### Branching Driveline Connection Lines

The Solver Configuration block in this example does not use any torque. It does share the angular velocity constraint from the branch point. Symbolically, the branching conditions on driveline connection lines are:

$$\omega_1 = \omega_2 = \omega_3 \dots$$

$$\tau_1 + \tau_2 + \tau_3 + \dots = 0 .$$

The sign convention is that torques flowing in are positive. Like all driveline axes, these have no inherent directionality. Torque flow directions are defined by overall system equations during simulation.

Torque and motion are transferred through the driveline from some driveshafts to others. Certain Simscape Driveline blocks require explicit directionality and represent it by designating one driveline connector port as the input *base* (B) and the other as the output *follower* (F), or some equivalent pair. When needed, positive relative motion of driveline axes or shafts is measured as follower relative to base.

---

**Motion Is Absolute** Except when relative motion is explicitly required, all motion in Simscape Driveline and Simscape models is measured in implicit absolute coordinates.

The Mechanical Rotational Reference and Mechanical Translational Reference blocks define the absolute zero velocity. If they are connected to a driveline axis, these blocks enforce this zero-motion state on that axis.

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# Basic Motion, Torque, and Force Modeling

### In this section...

“About Inertia, Motion, and Gears” on page 2-6

“Couple Rotational Motion with Gears” on page 2-6

“Couple Two Spinning Inertias with Simple Gear” on page 2-7

“Couple Two Spinning Inertias with Variable Ratio Transmission” on page 2-13

“Couple Three Spinning Inertias with Planetary Gear” on page 2-15

## About Inertia, Motion, and Gears

The purpose of a gear set is to transfer rotational motion and torque at a known ratio from one driveline axis to another. This section introduces you to modeling gears and using them to couple bodies rotating on driveline axes.

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**Note:** The concepts and examples of this section explain angular gears in relation to rotational motion and torque. Analogous rules apply to linear gears, and translational motion and force.

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## Couple Rotational Motion with Gears

A gear set consists of two or more meshed gears rotating together at some specified gear ratios. By convention, Simscape Driveline gear ratios are constant. The gear ratios determine how angular velocity and torque are transferred from one driveline component to another.

### Gear Coupling Rules

Ideal gears mesh and rotate together at a point of contact without frictional loss or slippage.

The simplest gear coupling consists of two circular gear wheels of radii  $r_1$  and  $r_2$ , spinning with angular velocities  $\omega_1$  and  $\omega_2$ , respectively, and lying in the same plane. Their connected shafts are parallel and carry torques  $\tau_1$  and  $\tau_2$ . The *gear ratio* of gear 2 to gear 1 is the ratio of their respective radii:  $g_{12} = r_2/r_1$ . The power transferred along either shaft is  $\omega \tau$ .



The gear coupling is often specified in terms of the number of gear teeth on each gear,  $N_1$  and  $N_2$ . The gear ratio of gear 2 to gear 1 is then  $g_{12} = N_2/N_1 = r_2/r_1$ .

The fundamental conditions on the simple gear coupling of rotational motion are  $\omega_2/\omega_1 = \pm 1/g_{12}$  and  $\tau_2/\tau_1 = \pm g_{12}$ . That is, the ratio of angular velocities is the reciprocal of the ratio of radii, while the ratio of torques is the ratio of radii. The transferred power, being the product of angular velocity and torque, is the same on either shaft.

The choice of signs indicates that the gears can spin in the same or in opposite directions. If the gears are external to one another (rotating together on their respective outside surfaces), they rotate in opposite directions. If the gears are internal to one another (rotating together with the outside of the smaller gear meshing with inside of the larger gear), they rotate in the same direction.

---

**Caution** Gear ratios in driveline model blocks must be strictly positive. Vanishing or negative gear ratios cause Simscape Driveline simulation to stop with an error at model initialization. If you need to reverse the relative rotation direction of a shaft connected to a gear, you can change the direction in the gear block dialog box.

---

## Couple Two Spinning Inertias with Simple Gear

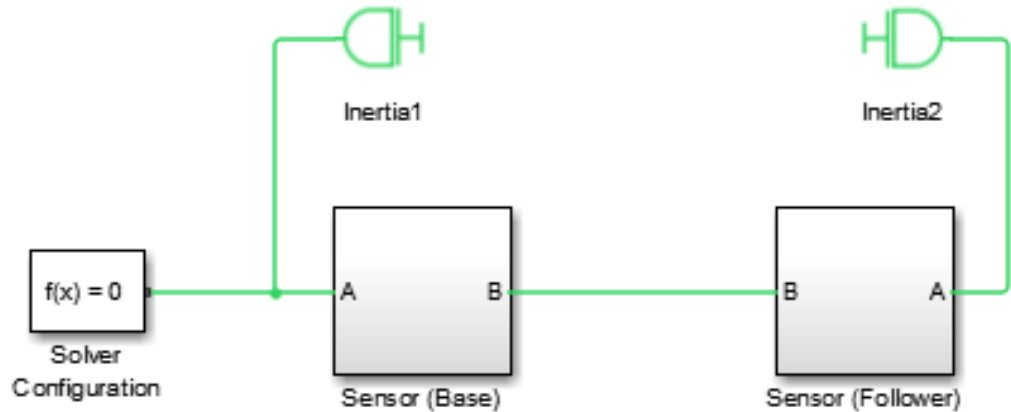
In this example, you couple two spinning inertias, first, along a single shaft (driveline axis), so that they spin with the same angular velocity; then spinning along two shafts and coupled by a gear so that they spin at different velocities; and finally, coupled by a gear and actuated by an external torque, spinning at different rates and experiencing different torques. You use the most basic Simscape mechanical and Simscape Driveline blocks, such as `Inertia`, `Simple Gear`, and `Solver Configuration`.

### Modeling Two Spinning Inertias

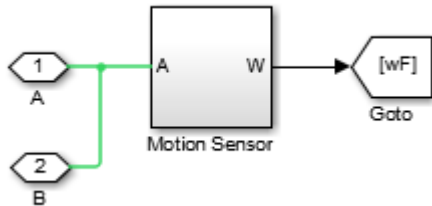
Create the first version of the simplest, nontrivial driveline model, two inertias spinning together along the same axis. Open the Simscape Driveline, Simscape, and Simulink block libraries and a new Simulink model window.

- 1 Drag and drop two `Inertia`, two `Ideal Rotational Motion Sensor`, two `Mechanical Rotational Reference`, and two `PS-Simulink Converter` blocks into the model window.
- 2 From the Simscape Utilities library, drag a `Solver Configuration` block. Every topologically distinct driveline block diagram requires exactly one instance of this block.

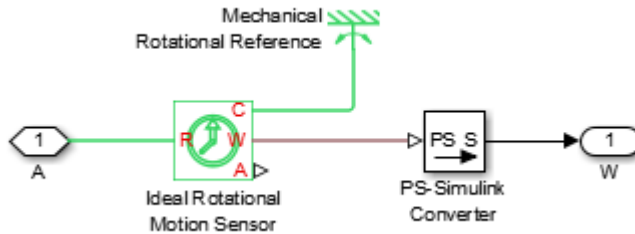
- 3 From the Simulink library, drag and drop a Scope, a Mux, and two pairs of Goto and From blocks. Connect the blocks as shown in the following figures. The sensor subsystems are arranged hierarchically.



**Model with Two Spinning Inertias**

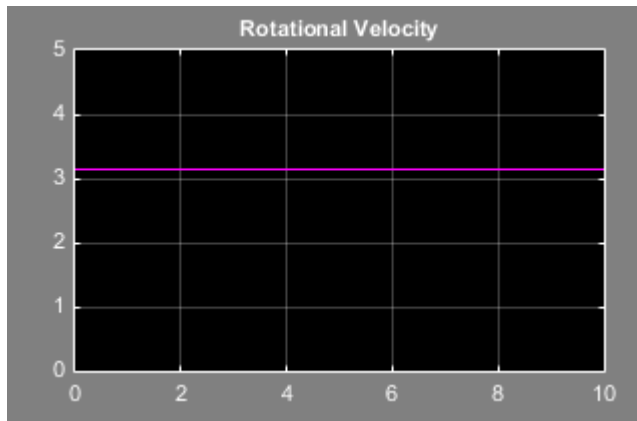


**Sensor Subsystem**



### Motion Sensor Subsystem

- 4 Open each Inertia block. In the **Variables** tab, select the **Rotational velocity** checkbox and set the **Value** parameter to  $\pi$  radians/second (rad/s). The connection line between the two Inertia blocks requires them to have the same rotational velocity.
- 5 Open the Scope block and start the simulation. The two angular velocities are constant at 3.14 radians/second.

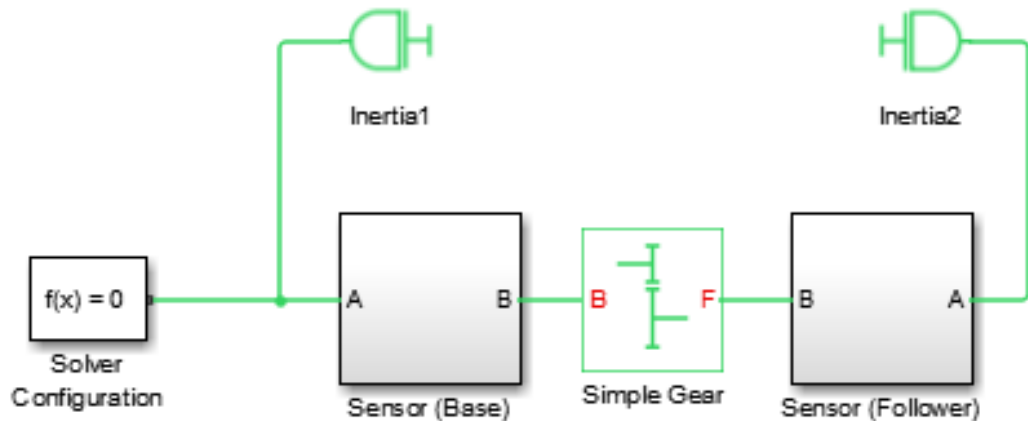


### Coupling Two Spinning Inertias with a Simple Gear

Now you modify the model you just created by coupling the two spinning inertias with a simple, ideal gear with a fixed gear ratio.

- 1 From the Simscape Driveline block library, drag and drop a Simple Gear block into your model. Open the block. Change the default follower-base gear ratio value to 1. Change the **Output shaft rotates** menu to **In same direction as input shaft** and

click **OK**. The simple gear then represents two gear wheels rotating together at the same rate in the same direction, with one wheel inside the other. Connect the blocks as shown in the following figure.



### Model with Two Spinning Inertias Coupled by a Gear

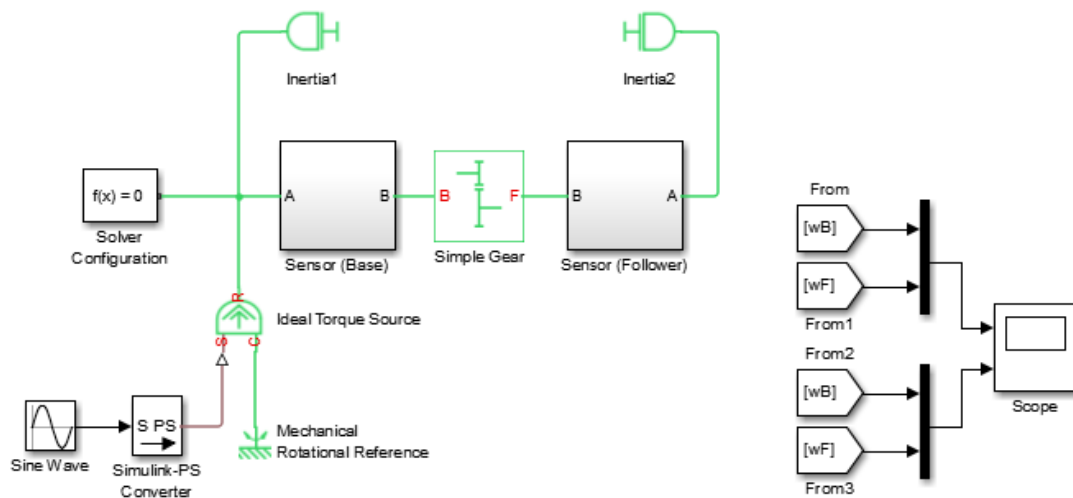
- Leave the initial angular velocities at  $\pi$  in the Inertia blocks.
- 2 Open the Scope and start the simulation. The two angular velocities are constant at 3.14 radians/second for both Inertias.
- 3 Change the **Output shaft rotates** menu back to **In opposite direction to input shaft**. The simple gear then becomes two wheels rotating together in opposite directions, with the two wheels meshed on their respective outer surfaces. Change initial velocity in Inertia2 to  $-\pi$ .
- 4 Restart the simulation. The two angular velocities are 3.14 and  $-3.14$  radians/second for Inertia1 and Inertia2, respectively. The second angular velocity is the same, but with opposite sign, because the two bodies are spinning in opposite directions.
- 5 Change the **Output shaft rotates** menu again to **In same direction as input shaft**.

### Torque-Actuating Two Coupled, Spinning Inertias

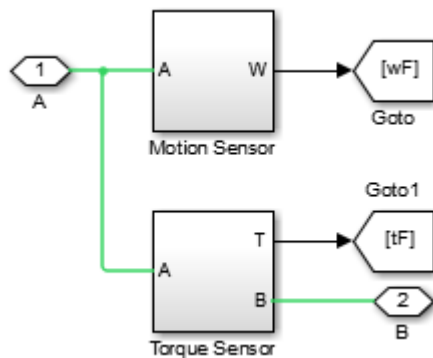
In the final version of the simple gear model, you actuate the inertias with an external torque instead of starting them with fixed initial angular velocities. The external torque

varies sinusoidally. You can find a completed version of this model in the `sdl_simple_gear` example model.

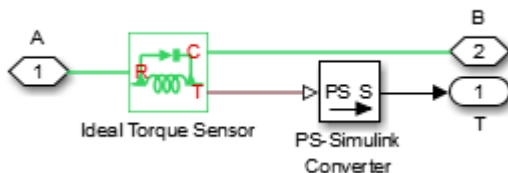
- 1 From the Simscape Foundation library, copy an **Ideal Torque Source** and two **Ideal Torque Sensor** blocks, plus a **Simulink-PS Converter** block and another **Mechanical Rotational Reference** block. From the Simulink library, drag and drop a **Sine Wave** block and two more pairs of **Goto** and **From** blocks.
- 2 Connect the blocks as shown in the following figures. Note that the Torque Sensor subsystems are arranged in parallel with the Motion Sensor subsystems inside the Sensor subsystem blocks. Set the initial velocities of both Inertias to zero. Modify the Scope block to add another axis for measuring the torques. Connect the other blocks as shown.



**Model with Two Spinning Inertias Coupled by a Gear and Actuated with Torque**



### Updated Sensor Subsystem



### Torque Sensor Subsystem

- 3 Open the Scope block and start the simulation.



The measured torques and angular velocities vary sinusoidally. As in the preceding models, the angular velocity of Inertia2 is half that of Inertia1. The torque in the second (follower) shaft is twice that in the first, as required by the laws of gear coupling.

If you change the **Output shaft rotates** menu to **In opposite direction to input shaft** in Simple Gear and restart the simulation, the same angular velocities and torques result, except that the values associated with Inertia2 and the second shaft are negative, because the second body and second shaft are spinning in opposite directions.

### Sensing and Actuating Motion and Torque

The mechanical sensor and source blocks that you use in the preceding models illustrate their dual nature. They act as driveline components themselves, but also let you inject and extract physical signals associated with motion and torque, including the correct

physical units. You can use these physical signals with other blocks in the Simscape physical modeling environment, or convert them to dimensionless Simulink signals for use in the nonphysical part of your model. Both sensor and source blocks have pairs of mechanical ports and are connected either in series with or across physical connection lines.

- Mechanical sensor and source blocks have both mechanical conserving ports  and physical signal ports .

Many Simscape Driveline blocks also feature a mix of mechanical conserving and physical signal ports.

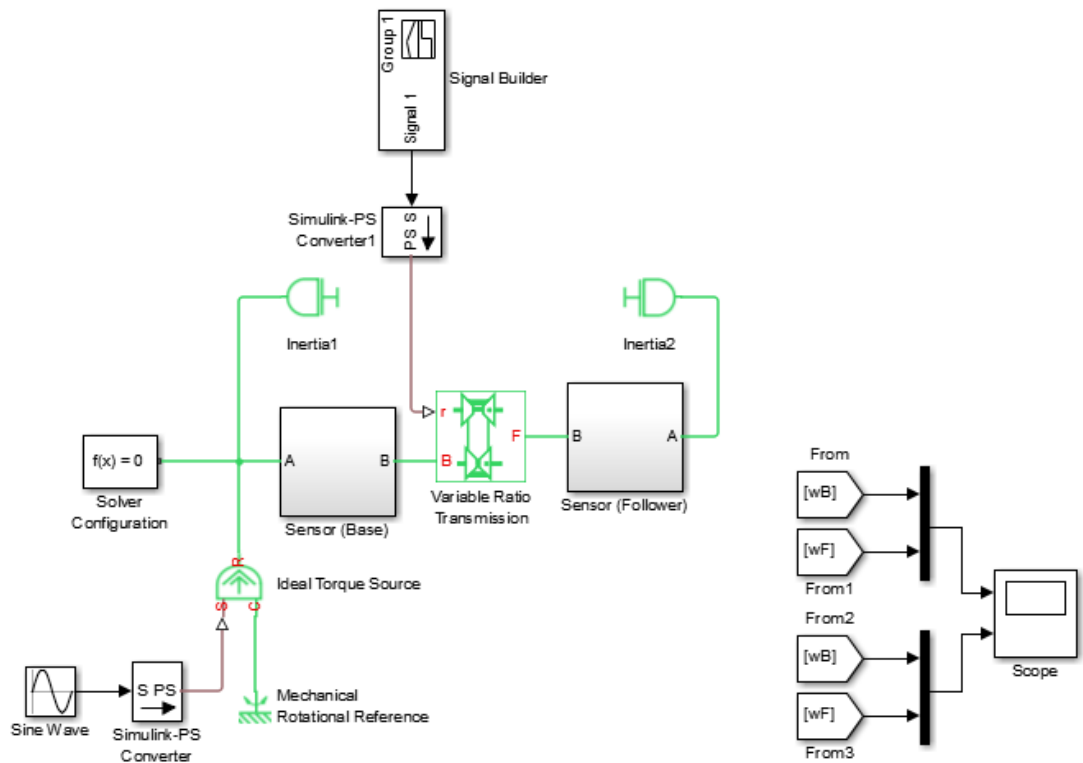
- An Ideal Torque Source injects torque along, or in series with, the driveline connection line. An Ideal Torque Sensor measures the torque flowing along, or in series with, the driveline connection line.
- An Ideal Rotational Motion Sensor reports the *difference* between the motions at its two connection ports.

If you want to extract the absolute motion at its R port, connect the C port to a mechanical reference block that grounds that port to zero motion.

## Couple Two Spinning Inertias with Variable Ratio Transmission

You can modify the simple gear model further by replacing the fixed-ratio gear with a transmission whose gear ratio varies in time. You specify the gear ratio variation with a Simulink signal converted to a unitless physical signal. Start with the simple gear model you built in the preceding section or by opening and editing the `sdl_simple_gear` example.

- 1 From the Simscape Driveline block library, drag and drop a **Variable Ratio Transmission** block and replace the Simple Gear block with it. Open the Variable Ratio Transmission block dialog box and make sure that the **Output shaft rotates** parameter is set to **In same direction as input** (the default setting). The two shafts will spin in the same direction. Ignore the other settings and close the block dialog box.
- 2 The Variable Ratio Transmission block accepts the continuously varying gear ratio as a physical signal Simulink signal through the extra physical signal input labeled **r**. For this example, create a variable signal for the gear ratio with a Signal Builder block from the Simulink block library and Simulink-PS Converter block. Build a signal that rises with constant slope from 1 to 2 over 10 seconds. Then connect the converted physical signal to the **r** port.



### Simple Variable Ratio Transmission Model

- Do not change the other, original settings of the simple gear model. Open the Scope and start the simulation.

The angular velocities and torques of the two shafts have the same signs. The ratios of angular velocities and torques start at 1, because the initial gear ratio is 1. As the gear ratio increases toward 2, the angular velocity of Inertia2 becomes smaller than that of Inertia1, while the associated torque in the second shaft becomes larger than that in the first shaft. Because of the changing gear ratio, the motion and the torques are no longer strictly sinusoidal, even though the actuating external torque is.

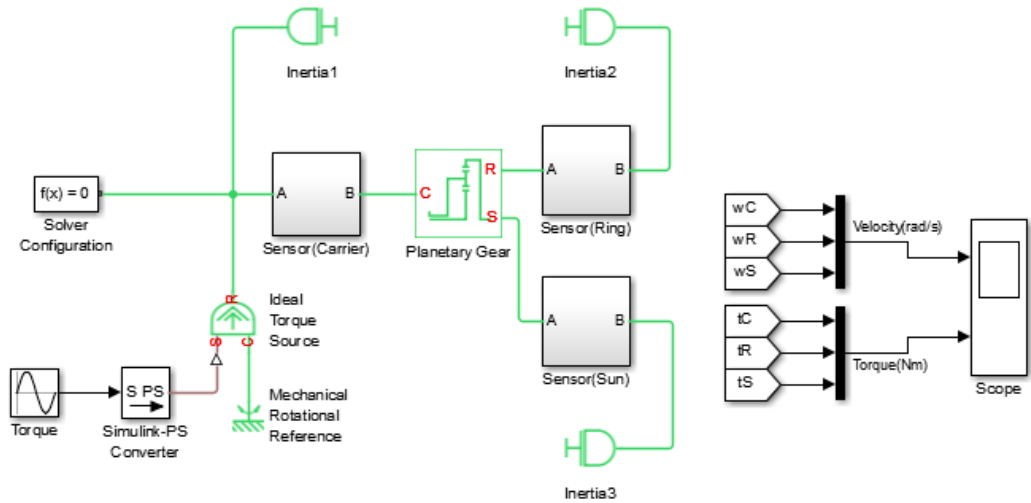
The `sdl_variable_gear` example is a full model of this type. To learn more about how to use variable gear ratios, consult the [Variable Ratio Transmission block reference page](#).



## Couple Three Spinning Inertias with Planetary Gear

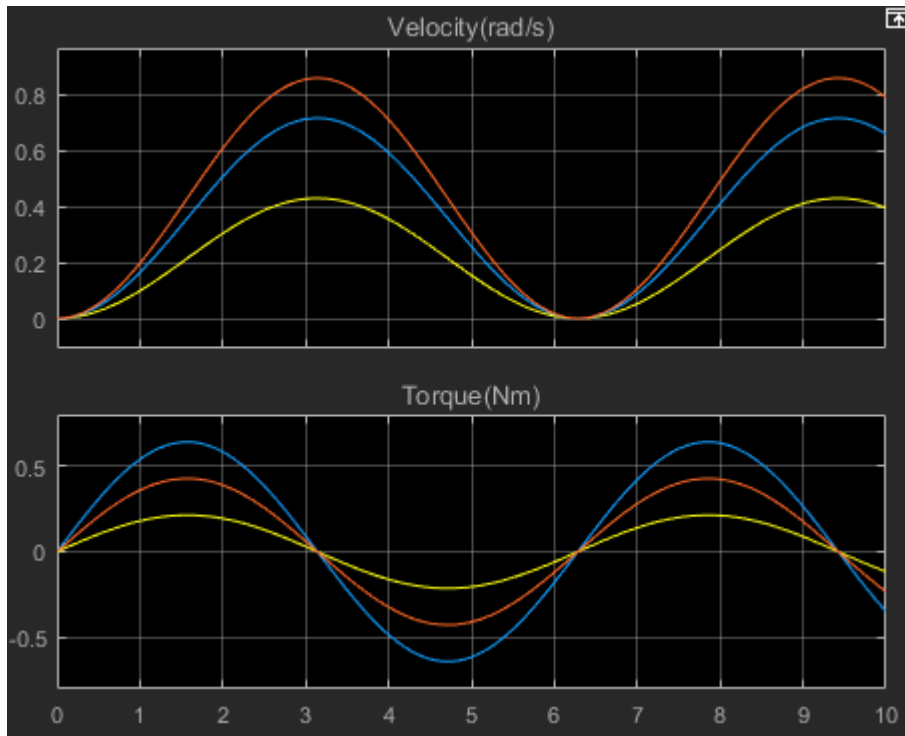
You can further modify the simple gear model and use it as a starting point for studying more complex gear sets. One of the most important complex gear sets is the planetary gear, which has three wheels, the ring, the sun, and the planet, all held in place by a common carrier body. The planetary gear is important because it is a common component in complex, realistic transmissions.

- 1** Start with the simple gear model you built or by opening the `sdl_simple_gear` example.
- 2** Replace the Simple Gear in your model with a **Planetary Gear** from the Simscape Driveline block library. A planetary gear splits input angular motion from the carrier between the ring and sun wheels, each connected to their respective bodies.
- 3** Copy the Sensor (Follower) subsystem, the connected **Inertia** block, and a **From** block.
- 4** Rename the sensor subsystems to match the gears that they attach to: carrier, ring, and sun. Rename the signals on the Goto and From block tags to match the gears that the signals represent:
  - For the carrier gear, rename the tags signals as  $w_C$  and  $t_C$ .
  - For the ring gear, rename the tags signals as  $w_R$  and  $t_R$ .
  - For the sun gear, rename the tags signals as  $w_S$  and  $t_S$ .
- 5** Add an input to each of the two **Mux** blocks.
- 6** Connect the blocks to form the new diagram as shown in the figure.

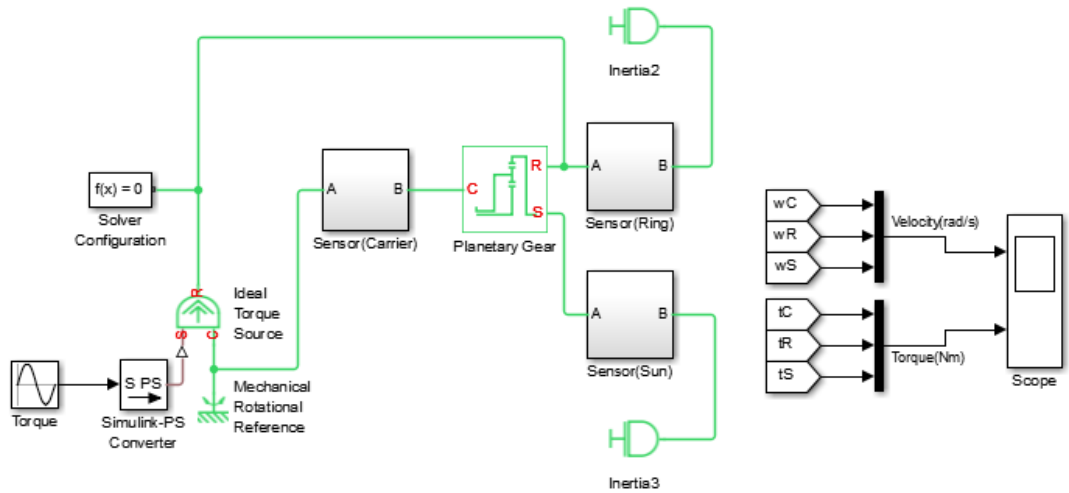


### Simple Planetary Gear Model

- Open the Scope and start the simulation to observe the angular velocities of the ring, carrier, and sun, from largest to smallest. The ratio of the ring to sun gear velocities is always 2.

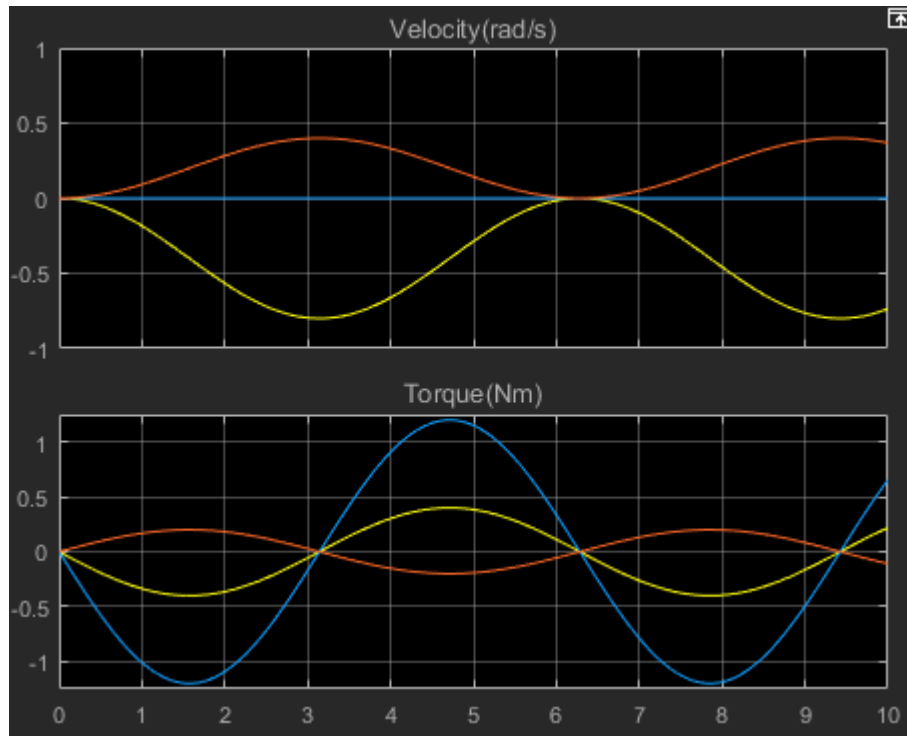


- 8** To see the ring and sun wheels spinning alone, you must lock the carrier. To do so:
- 1** Delete the connectors that connect the Sensor (Carrier) block and the Inertia block to the Solver Configuration block.
  - 2** Connect the Sensor (Carrier) block to the Mechanical Rotational Reference block.
  - 3** Delete the disconnected Inertia block.
  - 4** Connect the Solver Configuration block to the connector that comes from the R port on the Planetary Gear block.



### Simple Planetary Gear Model with Locked Carrier

- 9 Open the Scope and start your model. Observe the angular velocities of the ring, carrier, and sun.



The carrier, connected to Mechanical Rotational Reference, does not move. The ring is driven with a sinusoidal torque, and the sun responds by spinning in the opposite direction (ring and sun gear wheels are external to one another) at twice the rate. The ring wheel has twice the radius (or twice the number of teeth) as the sun, so it spins half as fast.

# Driveline Actuation

### In this section...

“About Torques, Forces, and Motion” on page 2-20

“Actuate a Driveline with Torques and Forces” on page 2-21

“Actuate a Driveline with Motions” on page 2-21

“Set Initial Conditions of Driveline Motion” on page 2-22

## About Torques, Forces, and Motion

From the torques and forces applied to driveline inertias and masses, a Simscape Driveline simulation determines the resulting motion from the driveline component connections and defining equations. However, a simulation can also accept motions imposed on a driveline and solve for the torques and forces to produce those motions. In general, a driveline simulation is a mixture of these two requirements, solving dynamics both forward (torque and force to motion) and inverse (motion to torque and force). Imposing motions and applying torques and forces to a driveline are together forms of mechanical *actuation*.

This section describes how to actuate drivelines with torques, forces, and motions, as well as how to set motion initial conditions. All of these actuation types (except for initial conditions) require physical signal inputs to define time-varying functions that carry physical units.

### Torque-Force Actuation and Motion Actuation Are Complementary and Mutually Exclusive

In all cases, you should exercise care as you apply a mixture of actuation types to a driveline and its degrees of freedom (DoFs). The complete effect of the actuation types must be such that:

- Driveline DoFs actuated by torques and forces are not also subject to motion actuation. (They can be subject to motion initial condition settings.)
- Driveline DoFs actuated by motions are not also subject to torque or force actuation.

For a Simscape Driveline model to successfully simulate nontrivial motion, torque and motion actuation types must exactly complement one another to account consistently for the motion of all the DoFs. If this criterion is not satisfied, one of these outcomes results:

- The motion of the driveline is trivial, staying in its initial motion state for the entire simulation.

- The actuation types are inconsistent with each other, and the simulation stops with an error.
- The actuation types leave the driveline motion underdetermined or overdetermined, and the simulation stops with an error.

For more about driveline simulation errors, see “Driveline Simulation Errors” on page 4-7.

## Actuate a Driveline with Torques and Forces

You can apply a torque to a rotational driveshaft, or a force to a translational driveshaft, in the following ways:

- Directly, with a **Ideal Torque Source** or **Ideal Force Source** block.
- Indirectly, with a dynamic element that generates torque or force. Such blocks include torque converters, clutches and clutch-like elements, and engines.

A torque or force source accepts a physical signal input and originates, from its mechanical conserving port, a mechanical connection line carrying that torque or force.

The Simscape Driveline simulation solves for the motion of the spinning or sliding driveshaft, given the torque or force that it is subject to. Therefore you cannot also subject that same driveshaft to motion actuation.

---

**Note:** A driveline actuated by a torque must have a nonzero inertia, represented by one or more connected **Inertia** blocks. A torque-actuated driveline without any inertia experiences a singular acceleration. (The analogous restriction holds for force actuation, masses, and **Mass** blocks.) In this case, the Simscape Driveline simulation stops with an error.

---

## Actuate a Driveline with Motions

You can apply a motion to a driveshaft directly, with an **Ideal Angular Velocity Source** or **Ideal Translational Velocity Source** block.

A motion source accepts a physical signal input and originates, from its mechanical conserving port, a mechanical connection line spinning or sliding with the specified motion.

The Simscape Driveline simulation solves for the torque or force carried by the spinning or sliding driveshaft, given its motion. Therefore you cannot also subject that same driveshaft to torque or force actuation.

### Set Initial Conditions of Driveline Motion

When driveline simulation starts, the complete driveline determines the initial motion of all driveshafts by a combination of constraints, motion sources, and initial condition settings. You set the initial conditions for the rotational and translational motion of inertias and masses in their respective Inertia and Mass blocks. The block default for initial velocities is zero (no initial motion).

For more information about constraints and degrees of freedom, see “Driveline Degrees of Freedom” on page 4-10.

---

**Note:** You must ensure that whatever initial conditions you impose on the Inertia and Mass blocks in your driveline are consistent with all of the driveline's constraints and motion sources. If an inconsistency occurs, Simscape Driveline simulation stops with an error at model initialization.

---

### Resolving Undetermined Motions in Complex Gears

A simple gear has two ports and imposes one constraint between them, leaving one independent DoF. Once one port is connected to a driveshaft, the motion of the other port's driveshaft is determined.

A complex gear has three or more ports and imposes one or more constraints among them. A complex gear can have any number of independent DoFs, including none.

If a simulation apportsions the initial motions of a complex gear in an unsatisfactory way, determine how you want the overall initial motion divided up and enforce that division by setting initial conditions on the connected Inertia and Mass blocks.

However you divide the initial motion among the gear shafts, ensure that this division is consistent with all constraints in your driveline, as well as any motion sources.

For more information about complex gears, see “Basic Motion, Torque, and Force Modeling” on page 2-6.



# Gear Coupling Control with Clutches

**In this section...**

“About Motion, Gears, and Clutches” on page 2-23

“Engage and Disengage Gears with Clutches” on page 2-23

“Brake Motion with Clutches” on page 2-28

“Model Friction Clutches at a Fundamental Level” on page 2-30

## About Motion, Gears, and Clutches

An important requirement of a practical drivetrain is the ability to transfer rotational motion and torque among spinning components at different speeds and gear ratios. In general, a single set of gears is not sufficient to accomplish this transfer. Clutches allow the drivetrain to selectively transfer motion, torque, and force at different gear ratios under manual or automatic control.

This section explains how to model and use clutches in driveline models without and with frictional losses and braking. On modeling various types of clutches and clutch-like elements, as well as clutch control, see “Specialized Clutches” on page 3-11.

## Engage and Disengage Gears with Clutches

A common problem in drivetrain design is transferring motion and torque at different fixed gear ratios. Drivetrains are typically designed to switch among a set of distinct gear ratios. Implementing the switch from one gear ratio to another requires gradually disengaging one set of driveline couplings and engaging another set. Clutches allow you to gradually engage and disengage driveline shafts from one another.

The `Disk Friction Clutch` block represents a standard surface friction-based clutch that models this behavior. You also can model clutches in greater detail using the `Fundamental Friction Clutch` block, which requires you to specify the static and kinetic clutch friction more completely. See also “Model Friction Clutches at a Fundamental Level” on page 2-30.

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**Note:** You can model continuous motion-torque transfer with the `Torque Converter` block, which simulates fluid viscosity instead of surface friction and never locks.

---

### How a Clutch Works

A clutch makes two shafts spinning at different rates spin at a single rate by applying forces that tend to accelerate one shaft and decelerate the other. The most common way for a clutch to accomplish this action is with surface friction. Such a clutch can operate in one of these modes of motion:

- *Disengaged*: the clutch applies no friction at all.
- *Engaged but unlocked*: the clutch applies kinetic friction, and the two shafts spin at different rates.
- *Engaged and locked*: the clutch applies static friction, and the two shafts spin together.

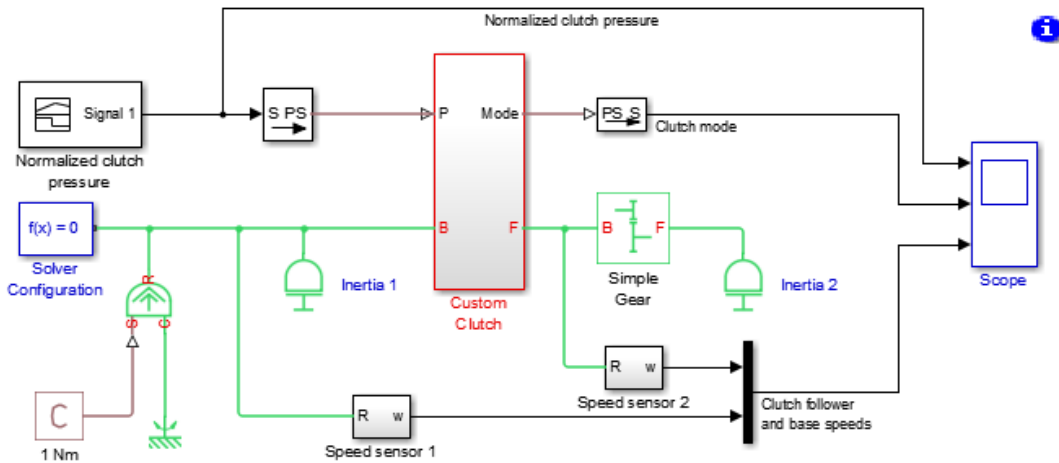
A clutch consists of mated frictional surfaces overlapping one another and connected on either side to a shaft. If the clutch is disengaged, the frictional surfaces have no contact and the shafts spin independently. To engage the clutch, contact between two surfaces is induced by applying clutch pressure (a force normal to the surfaces). The two surfaces in contact and moving relative to one another experience kinetic friction, which causes them to narrow their relative velocity. The friction acts to reduce the relative motion between the two clutch plates and their connected shafts. At some critical combination of reduced relative speed and pressure (normal force), the clutch locks, so that the two shafts are spinning at the same rate. The shafts remain locked together as long as the transmitted torque remains less than the static friction, which is proportional to the applied normal force. If the clutch unlocks but is still engaged, it again applies kinetic rather than static friction.

The transition between unlocked and locked states is discontinuous. Modeling a clutch locking or unlocking event requires searching for the correct combination of pressure and torque acting on the clutch. The locking and unlocking events are determined during simulation by repeated and accurate zero-crossing detection. On simulating events and solving constraints together with dynamics in Simscape models, see “Desktop Simulation”.

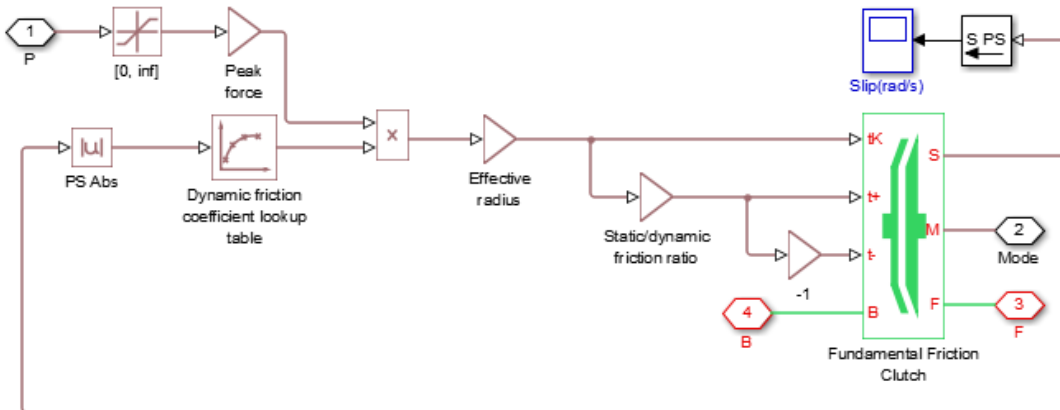
### Engaging and Disengaging a Gear with a Clutch

Construct a simple model that simulates a gear being engaged, then disengaged, by a clutch. Torque and motion are transferred from one shaft to another over a finite time interval. You can start with the simple gear model created in the preceding section or with the `sdl_simple_gear` example, creating a simpler version with the Disk Friction Clutch.

A more complex version, shown here, is the `sdl_simple_clutch` example. It uses a clutch subsystem containing the Fundamental Friction Clutch instead.



### Simple Clutch Model with Programmed Clutch Pressure



### Custom Clutch Subsystem

- The clutch subsystem is positioned between Inertia1 and Simple Gear and reports the clutch mode (forward, reverse, locked).

- The **PS Constant** block replaces the sinusoidal signal as the torque input. The torque sensor blocks are omitted.
- **Simulink-PS Converter** and **PS-Simulink Converter** blocks communicate between physical signals in the Simscape environment and Simulink blocks such as Signal Builder and Scope.
- The Signal Builder block provides the programmed clutch pressure signal, normalized between 0 and 1, as shown in the following table. This signal is converted to a physical pressure inside the clutch subsystem.

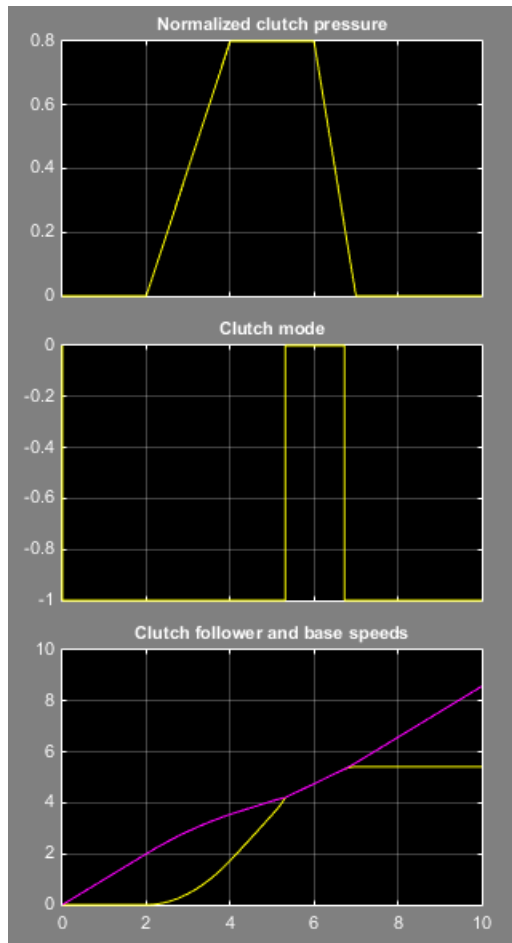
Time Range (Seconds)	Signal Value
0 – 2	0
2 – 4	0 – 0.8 with constant slope
4 – 6	0.8
6 – 7	0.8 – 0 with constant slope
7 – 10	0

Open the Scopes and start the simulation. The normalized clutch pressure signal follows the profile that you created in Signal Builder and determines the model's behavior.

- 1 From 0 to 2 seconds, the velocity of Inertia1 increases linearly because it is subject to a constant torque.
- 2 At 2 seconds, the clutch begins to engage, and Inertia2 begins to spin. The velocity of Inertia1 continues to rise, although at a slower rate, because the two inertias now share the external torque.
- 3 At 4 seconds, the pressure reaches its maximum. At about 5.32 seconds, the clutch locks. The driveshafts connected by the clutch now spin together. Inertia1 and Inertia2 continue to speed up at constant accelerations, Inertia2 at half the velocity of Inertia1.
- 4 At 6 seconds, the clutch begins to disengage as the pressure drops. Inertia1 and Inertia2 continue to accelerate with the applied torque.

The clutch unlocks at about 6.73 seconds and fully disengages at 7 seconds. (The clutch unlocks a little before completely disengaging because the pressure, even before vanishing, becomes too small to maintain the lock.) Inertia1 is still accelerating. But Inertia2, now free of the driveshaft and its torque, no longer accelerates and instead spins at a constant rate without frictional loss.

While the two shafts are locked, between 5.32 and 6.73 seconds, Inertia1 and Inertia2 spin in a fixed 2:1 ratio, because of the Simple Gear.



#### How the Clutch Mode Indicates Locking and Unlocking

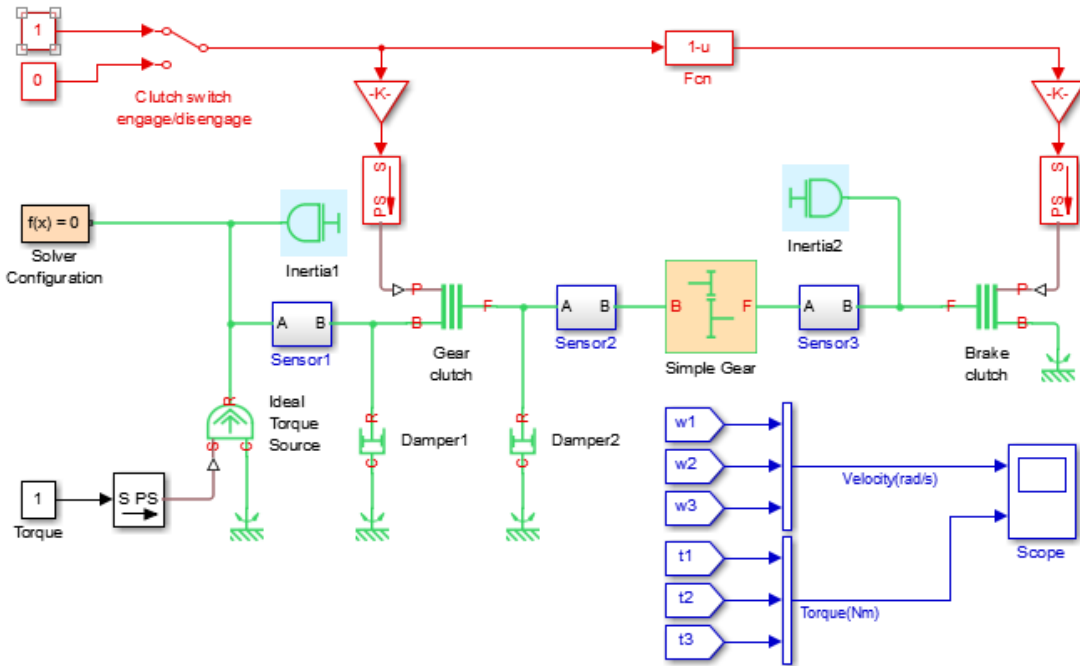
The Clutch mode signal indicates the relative motion of its two connected shafts. From 0 to 5.32 seconds, the two shafts are moving relative to one another. The follower (driven) shaft is slower than the base (drive) shaft, so the mode signal is  $-1$ . Once the two shafts lock, their relative velocity is 0, and the mode signal switches to 0. At 6.73 seconds, they unlock, and the drive (base) shaft starts accelerating faster than the driven (follower) shaft. The mode signal switches back to  $-1$ .

## Brake Motion with Clutches

A special case of transferring motion occurs when you want to brake the spinning of a driveline component, slowing it down until it stops. The common way to brake the motion is to couple the spinning component to a rotational ground. You can represent a rotational ground with a Mechanical Rotational Reference block from the Simscape Foundation library. Because a rotational ground cannot move, a driveline axis locked to a rotational ground also cannot move. You can implement the gradual engagement or disengagement of a driveline component with a rotational ground using a clutch, just as you use a clutch to gradually couple or uncouple two spinning shafts.

### Braking with a Double-Clutch System

The `sdl_clutch_engage` example model builds on the preceding tutorial models and features two clutches, one of which acts as a brake. The model also includes frictional damping for greater realism. The simulation time is set to `inf` (infinity). For simplicity, the Disk Friction Clutch block is used.



### Simple Clutch Model with Brake Clutch

This model uses the basic structure of inertia—clutch—gear—inertia. The first body, Inertia1, is driven by an external torque, and the initial velocities are 0. There is, however, another clutch for the second body, Inertia2, that can couple Inertia2 to the Mechanical Rotational Reference and bring it to a stop. Another new feature is the switching assembly based on the clutch switch. You can change this switch to apply a constant clutch pressure signal to either clutch 1 (the gear clutch) or clutch 2 (the brake clutch). (The Fcn 1—u block ensures that the full clutch pressure is applied to either one or the other, but not both at once.) The Damper blocks apply viscous (velocity-dependent) friction to the spinning of Inertia1 and Inertia2.

- 1 Start the model with the Clutch Switch set to 1. The clutch pressure is then applied to the Gear clutch, which engages and locks the driver and driven shafts and causes them to rotate at the same velocity.

Inertia2 is on the other side of the Simple Gear. The angular velocity of Inertia1 is twice that of Inertia2 because the gear ratio of the Simple Gear block is 2, follower to base. In this switch mode, no clutch pressure is applied to Brake Clutch, which remains unengaged.

After an initial transient, the system settles into a steady state of motion where the external torque balances the friction losses.

- 2 With the simulation running, change the Clutch Switch to 0 to disengage the gear clutch and engage the brake clutch. The system undergoes another transient while the Gear clutch disengages and Brake clutch engages.

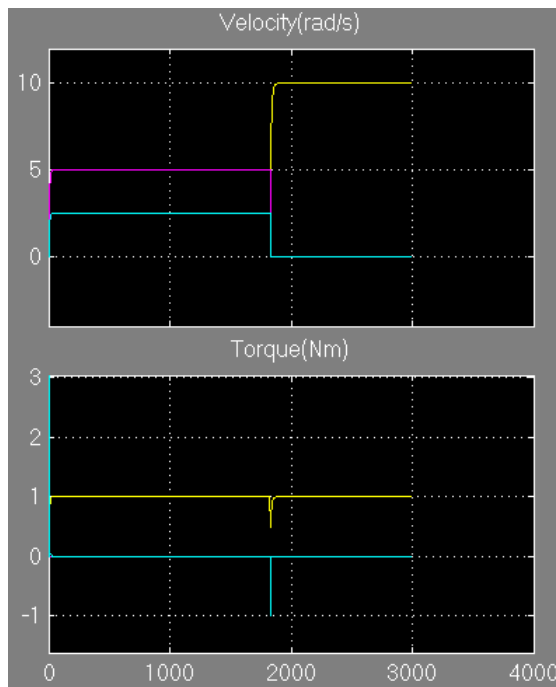
The angular velocity of Inertia1 and the driver shaft settles down to a new steady state of 10 radians/second, twice its old speed.

Because the Gear clutch is now disengaged, the driven shaft and Inertia2 are no longer subject to a driving torque through Gear clutch. But the Brake clutch is engaged and couples Inertia2 to the immobile Mechanical Rotational Reference. Once engaged, the kinetic friction of the Brake clutch brings the driven shaft and Inertia2 to a stop.

To see the transient behavior at simulation start and when you switch the clutches:

- 1 Start the simulation and let it run for a short time. Then switch Clutch Switch to the other mode.
- 2 After a short time, stop the simulation. Use the **Autoscale** feature of the Scopes to capture the entire simulation sequence. The transients from the starting behavior and the switching transition are visible.

For example, in these plots, the model was started with Clutch Switch set to 1 (Gear clutch locked, Brake clutch disengaged, no braking). The velocities quickly climbed to their steady-state values. Then Clutch Switch was changed at about 1830 seconds of simulation time. Gear clutch disengaged and Brake clutch engaged, braking Inertia2. The driver shaft's angular velocity rose from 5 to 10 radians/second. The driven shaft's angular velocity dropped from 5 to 0, and Inertia2's angular velocity dropped from 2.5 to 0.



### Model Friction Clutches at a Fundamental Level

The `Disk Friction Clutch` block requires only a single pressure signal to modulate the kinetic friction. You fix all its other characteristics before starting simulation.

Modeling a friction clutch at a fundamental level requires direct control over the kinetic and static friction torques. The `Fundamental Friction Clutch` block gives you that control. With this block, you must specify, by either external signals or internal dynamics, the clutch's kinetic friction and static friction limits (positive and negative) as functions of time.



# Gears, Clutches, and Transmissions

**In this section...**

“About Gears, Clutches, and Transmissions” on page 2-31

“Model a Two-Speed Transmission with Braking” on page 2-32

“Model a CR-CR 4-Speed Transmission Driveline with Braking” on page 2-38

## About Gears, Clutches, and Transmissions

In a real drivetrain, you couple an input or drive shaft to one of many output or driven shafts, or to one driven shaft with a choice of several gear ratios. The drivetrain then requires several clutches to switch between gears. You couple one of the driven shafts or one of the gear sets by engaging one of the clutches. You then switch to another output shaft or another gear ratio by disengaging one clutch and engaging another.

You can also engage more than one clutch at a time to use multiple gear sets simultaneously. Transmissions engage multiple gear sets at the same time to produce a single effective gear ratio, or *drive ratio*. Changing gears requires disengaging one set of clutches and engaging another set. You can specify the set of clutches to engage and disengage for each gear ratio in a *clutch schedule*. Designing a clutch schedule and shaping and sequencing the clutch pressure signals frequently constitute the most difficult part of transmission design. A realistic transmission model must also include losses due to friction and imperfect gear meshing.

This section explains how to model transmissions, by creating a transmission model from gears and clutches. A predesigned transmission, the CR-CR 4-speed transmission, is the basis of a second example.

### Some Important Transmission Design Principles

When creating or modifying a transmission model:

- Connect inertia blocks with nonzero inertia values to gear shafts for realistic simulation and preventing acceleration singularities when torques are applied.
- Make sure that the clutch schedule for your transmission specifies those clutches that must be engaged and those that must be free at any instant for the transmission to be properly in gear. Set all clutch pressures to 0 only if you want to disengage the transmission completely (place it in neutral).

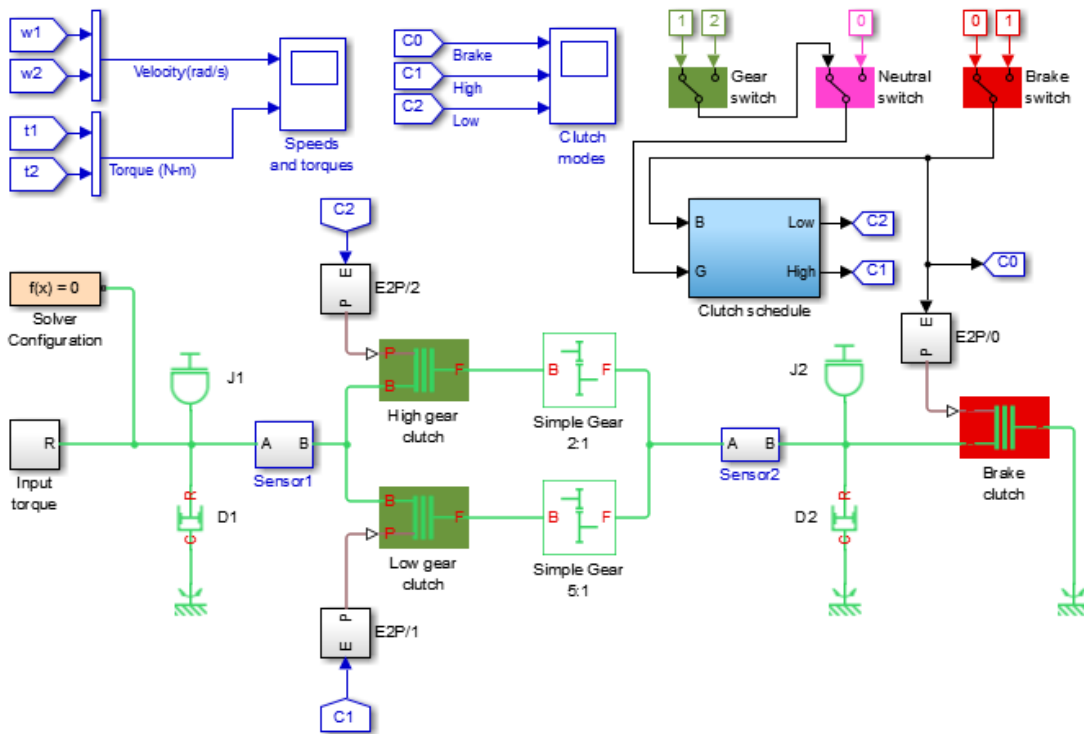
Do not engage any more or fewer clutches than needed, at any time during simulation.

- If you want to redesign a transmission by adding or removing gears, you must consider whether you also need to add or remove clutches and redesign the clutch schedule. You also might need to add or remove gear shaft inertias.

On the relationship clutch pressure signals to solver choices and settings, see “Driveline Simulation Performance” on page 4-2.

## Model a Two-Speed Transmission with Braking

The example model `sdl_simple_transmission` contains a driveline system that makes up a simple yet complete transmission.



Simple Transmission with Two Gear-Clutch Pairs and Braking

The model is built on the `sdl_clutch_engage` example model. This model contains two driveline shafts or axes, with a constant actuating torque of 1 newton-meter applied to the driver shaft. Both the driver and the driven shafts are subject to small viscous damping torques (blocks D1 and D2). The viscous torque constant  $\mu$  is 0.001 newton-meters/(radians/second). In the steady state, the driving and damping torques balance one another; the two shafts spin at constant rates, the driver shaft at  $(1 \text{ N}\cdot\text{m})/(0.001 \text{ N}\cdot\text{m}/(\text{rad}/\text{s})) = 1000 \text{ rad}/\text{s}$ . (If braking is engaged, the driven shaft is stopped.) There are now two selectable gears to couple the two axes, instead of one. (On modeling viscous losses with nonideal gear bearings instead of dampers, see “Specialized Gears” on page 3-7.)

This transmission model couples the gears in a simple way, with each gear and the brake associated with its own respective clutch. Coupling one gear requires engaging and locking its corresponding clutch, while ensuring that the other two clutches are disengaged. The brake clutch is directly activated by its own switch.

### Setting Up the Gears, Clutches, and Brake

The two gears are Simple Gear blocks with different gear ratios, each connected in series with its corresponding clutch. The two gear-clutch pairs are coupled in parallel. This parallel assembly then couples the driver shaft to the driven shaft, with their two spinning inertias. One gear is a “low” gear, the other a “high” gear. Following common usage for automobile gears, the “low” and “high” labels refer to the angular velocity ratios.

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**Note:** The ratio of speeds in a gear is the *reciprocal* of the gear ratio.

---

- The low gear is the Simple Gear 5:1 block, which can be coupled by engaging its corresponding clutch, modeled by the Low gear clutch block. The gear ratio is 5:1, so that the ratio of output to input (follower to base) angular speeds is 1/5. Such a gear has a high torque transfer ratio of 5, from base to follower. In an automobile, a low gear like this is used to accelerate the vehicle from a stop by transferring a large torque down the drivetrain from the engine.
- The high gear is the Simple Gear 2:1 block, coupled by engaging its own clutch, represented by the High gear clutch block. The gear ratio is 2:1, and the angular velocity ratio of follower to base is 1/2, or 5/2 times the ratio in the low gear. The torque transfer ratio is only 2 from base to follower. An automotive high gear is used for milder acceleration or coasting once a vehicle is moving at a significant speed.

The vehicle acceleration generated by this gear is less than that generated by the low gear.

Switching on either the Neutral switch or the Brake switch disengages both gear clutches. In either case, the driver shaft continues to spin, approaching a steady velocity, subject to the competing driving and damping torques.

- Switching the transmission to neutral leaves the brake clutch disengaged and the driven shaft free to spin. But without a driving torque, damping gradually brings the driven shaft to a stop.
- Switching the brake on immediately locks the brake clutch and stops the driven shaft.

This simple transmission is based on mapping each transmission state one-to-one with an engaged clutch. You cannot engage more than one clutch at a time without creating conflicts between gear ratios or between the driver shaft and the rotational ground.

### Controlling the Transmission State with a Clutch Schedule

The requirement to engage a certain clutch or set of clutches and disengage others, both to implement transmission functions and to avoid motion conflicts between gears, is the basis for all clutch schedules. Simulink provides a number of ways to implement clutch schedules, depending on the complexity of the transmission and how much realism you require for the clutch pressure signals.

---

**Caution** You must check every transmission's clutch schedule to implement its transmission states correctly and to avoid motion conflicts among gear sets. You must also check clutch pressure signal profiles to make sure that any transmission's clutches are engaged, locked, unlocked, and disengaged in a realistic and conflict-free manner. Unphysical or conflicting clutch schedules and clutch pressure signals lead to simulation errors in Simscape Driveline models and can damage or destroy a real transmission.

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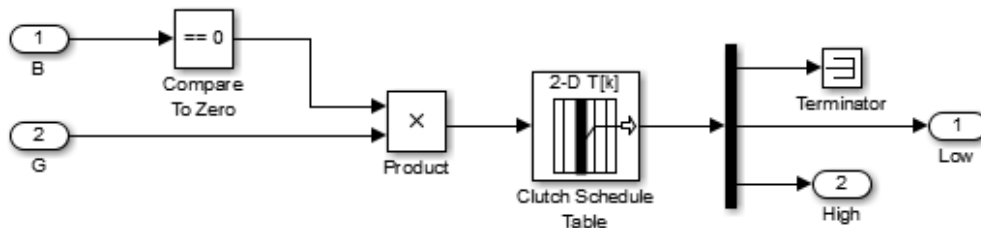
For the `sdl_simple_transmission` model, avoiding such conflicts leads to a unique clutch schedule.

### Clutch Schedule for the Simple Two-Speed Transmission

Transmission State	Brake Clutch State	Low Gear Clutch State	High Gear Clutch State
Neutral/Braked	Disengaged/ Locked	Disengaged	Disengaged

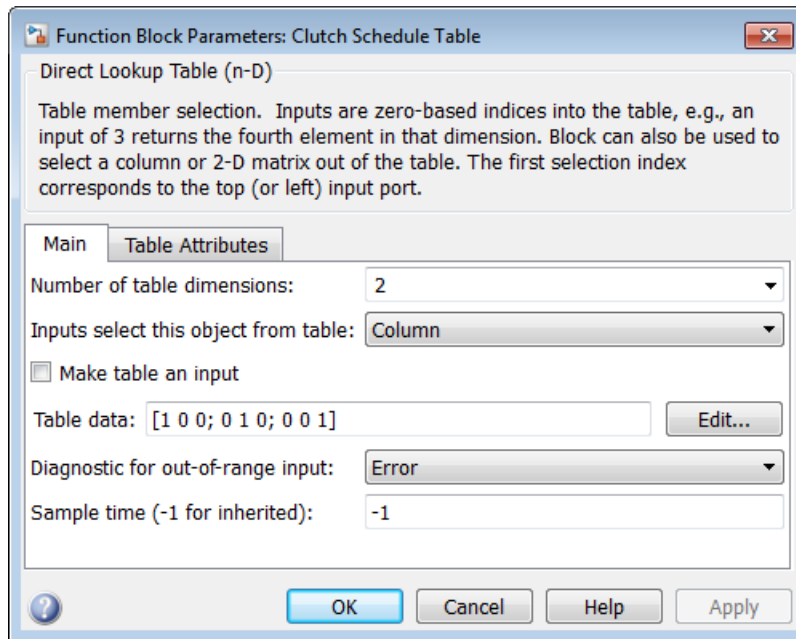
Transmission State	Brake Clutch State	Low Gear Clutch State	High Gear Clutch State
Low Gear	Disengaged	Locked	Disengaged
High Gear	Disengaged	Disengaged	Locked

The model contains a simple Clutch Control subsystem to implement the clutch schedule and to output the clutch pressure signals to lock each clutch as needed.



### Clutch Control Subsystem for Simple Transmission Model

In this simplified and unrealistic clutch control model, the clutch pressure signals are constants: 1 to engage and lock a clutch; 0 to disengage it. (A clutch pressure signal is normalized to equal 1 when the surface friction force equals the peak normal force specified in the clutches.) For each transmission state, the table of these constants is contained in the Clutch Schedule Table block, customized from the `Direct Lookup Table (n-D)` block. Open the Clutch Schedule Table block to see this table.



The table is indexed in both row and column, starting from zero. An input signal of 0 causes the block to output the first column of table values; a value of 1 outputs the second column; a value of 2, the third column. The Terminator block prevents the first element of each column (that is, the entire first row of values) from leaving the subsystem.

The first column applies zero pressure to the two gear clutches. The second column applies full pressure to the low gear clutch and zero pressure to the high gear. The third column applies full pressure to the high gear clutch and zero pressure to the low gear.

These different table columns are activated by changing the positions of the Gear switch and Neutral switch, while leaving the Brake switch off. With the neutral switch off, the Gear switch signal can pass to the Clutch Schedule Table. This signal is 1 for the low gear and 2 for the high gear. Turning the neutral switch on prevents the Gear switch signal from reaching the clutch controller.

Turning on the Brake switch also prevents the Gear switch signal from reaching the clutch controller. At the same time, switching on the brake directly applies locking pressure to the Brake clutch.

## Running the Model, Switching Gears, and Braking

To see how gear switching works:

- 1 Start the model and open the two scopes.

Its initial transmission state is low gear, with the Gear switch to the left, transmitting a signal value of 1. The driven shaft spins at one-fifth the rate of the driver shaft, in the opposite direction.

- 2 Change the Gear switch from low to high (left to right, signal value of 1 to 2), and observe how the driven shaft velocity increases in the Speeds and torques scope.

The driven-to-driver ratio is now one-half. (The driver shaft velocity decreases slightly, because it experiences the damping torque on the driven shaft differently depending on which gear is engaged.)

- 3 Change the Gear switch back to low (right to left, 2 to 1), then observe that the driven shaft again spins more slowly.

At the same time, while you switch the gears back and forth, the clutches, as shown in the Clutch modes scope, switch from Low gear clutch being locked, to the High gear clutch being locked, and back. When one is locked, the other is unlocked.

- 4 Apply immediate braking by switching the Brake switch to on (left to right, 0 to 1). The driven shaft comes to an immediate and complete stop. The driver shaft continues to spin.

Then release the brake, moving the Brake switch to off (right to left, 1 to 0).

- 5 Change the Neutral switch to the right position, transmitting a signal value of 0.

The two gear clutches unlock and disengage. The Brake clutch remains unengaged. The driven shaft, subject to very light damping, now slows gradually.

- 6 By turning the Brake switch to on, you can switch the Brake clutch to the locked mode and bring the driven shaft to a stop. The driver shaft continues to spin.

## Adding Realistic Clutch Signals

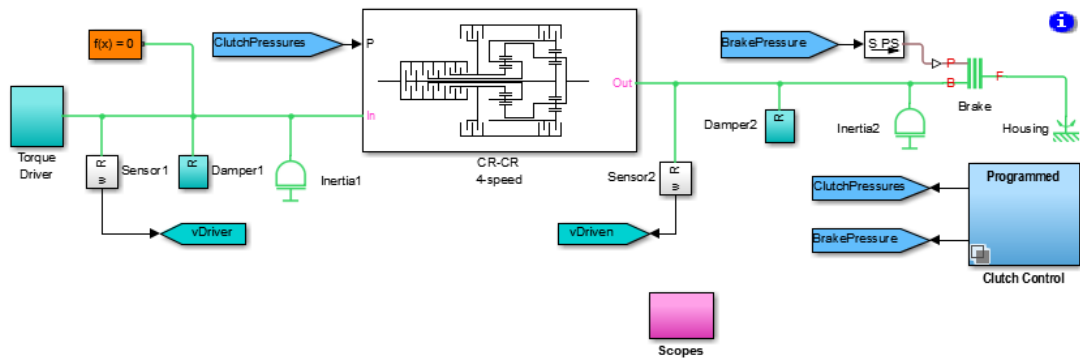
The clutch control subsystem of this example is adequate for a simple model, but not realistic. It contains unrealistic clutch pressure signals that rise and fall sharply. A full clutch control model requires realistic clutch pressure signals that rise from and fall back to zero in a smooth way. Greater realism requires a potentially more complex model. It is critical for the Simscape and Simulink solvers to determine transmission motion for

exactly two clutches to always remain locked, or for all four to be unlocked, at any time in the simulation. Changing the transmission's gear settings while maintaining this requirement is an example of the central problem of transmission design.

For transmission and car examples with smoothed clutch pressure signals, see “Model a CR-CR 4-Speed Transmission Driveline with Braking” on page 2-38 and “Complete Vehicle Model” on page 2-43.

## Model a CR-CR 4-Speed Transmission Driveline with Braking

The `sdl_crcr` example model builds on the previous clutch and transmission models with a more realistic transmission. It uses a CR-CR 4-Speed transmission subsystem to transfer motion and torque from one shaft and inertia to another.



### CR-CR 4-Speed Transmission Model

A Torque Driver subsystem feeds a constant driving torque from a torque source to the driver shaft (Inertia1). Two damping subsystems apply heavy and light viscous friction to the driver and driven shafts, respectively. The two Scopes measure the shaft velocities and clutch pressures, respectively. The model pre-load function defines essential parameters in the workspace. (You can view this pre-load function. Open the model **File** > **Model Properties** > **Model Properties** dialog box. Then, click the **Callbacks** tab).

The CR-CR 4-Speed transmission subsystem couples the driver to the driven shaft (Inertia2). If the transmission is disengaged, a brake clutch and fixed housing allow you to brake the driven shaft. When you first open the model, the Clutch Control subsystem contains a set of programmed clutch signals for shifting the CR-CR transmission through a preconfigured gear and braking sequence over 30 seconds.



For clarity, the model's major signal buses have been bundled as vectors and directed using Goto and From blocks. The Scopes are collected in the Scopes subsystem for convenience.

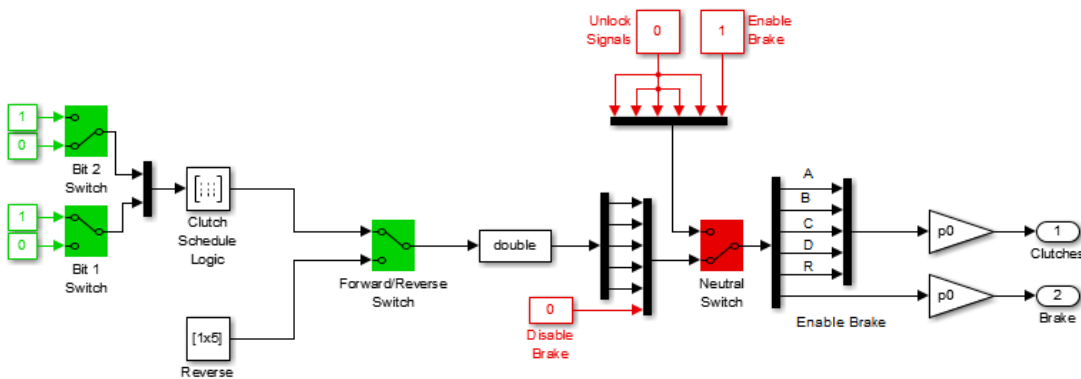
### Replacing Programmed with Manually Controlled Clutch Pressures

The model represents the clutch control system using a Variant Subsystem block. This block provides two clutch control modes, or *variants*: manual and programmed. To switch to manual control mode:

- 1 Right-click Clutch Control.
- 2 In the context menu, select **Variant > Override using > Variant1 (Manual)**
- 3 Double-click Clutch Control and then Manual. During simulation, the Manual subsystem provides direct control over gear changes.
- 4 In the Simulink toolbar, change the simulation time to `inf`.
- 5 Run simulation.

To change gears during simulation, use the Manual Switch blocks. Bit 2 Switch controls clutches A and B, while Bit 1 Switch controls clutches C and D. The table summarizes the clutch responses when toggling a switch up or down.

Manual Switch Block	Switch-Up Response	Switch-Down Response
Bit 2 Switch	Lock clutch A, release clutch B	Release clutch A, lock clutch B
Bit 1 Switch	Lock clutch D, release clutch C	Release clutch D, lock clutch C



### Manual Clutch Control for CR-CR Transmission

### Configuring the CR-CR Transmission Subsystem

The CR-CR 4-Speed transmission subsystem uses certain parameters set to realistic values. These parameters are referenced to variables defined in the workspace when the model opens. These variables are used in the four CR-CR Clutch blocks A, B, C, and D.

#### CR-CR 4-Speed Transmission Clutch Variables

Workspace Variable	Description
num_fric_surf	Number of frictional surfaces in each clutch
eff_tor_rad	Effective torque radius in each clutch (m)
peak_normal	Peak normal force on clutch surfaces (N)
fric_coeff (matrix)	Kinetic friction coefficient as a function of the relative angular velocity of the clutch shafts

The clutch schedule of the CR-CR transmission subsystem is a table of gear settings, clutch lockings, and gear ratios. There are four distinct (forward) gear settings, each with a different effective gear ratio. For the transmission to be properly engaged and transmit torque and motion, exactly two clutches must be locked at any instant. Unlocking all the clutches simultaneously puts the transmission into neutral (no motion or torque transfer). The transmission contains two planetary gears, five clutches, and four inertias.

#### Clutch Schedule for the CR-CR 4-Speed Transmission

Gear Setting	Clutch A State	Clutch B State	Clutch C State	Clutch D State	Clutch R State	Drive Ratio
1	<i>L</i>	F	F	<i>L</i>	F	$1 + g_o$
2	<i>L</i>	F	<i>L</i>	F	F	$1 + g_o/(1 + g_i)$
3	<i>L</i>	<i>L</i>	F	F	F	1
4	F	<i>L</i>	<i>L</i>	F	F	$g_i/(1 + g_i)$
Reverse	F	F	F	F	<i>L</i>	$-g_i$

- *L* = locked
- F = free
- $g_i$  = Input Planetary Gear ring-to-sun gear ratio

- $g_o$  = Output Planetary Gear ring-to-sun gear ratio

The main model's Damping subsystems use these variables for frictional damping of the driving (engine) and driven shafts coupled across the transmission.

### Drive Shaft Damping Coefficients

Workspace Variable	Description
eng_damping	Driver (engine) shaft kinetic friction coefficient (N-m/(rad/s))
driven_damping	Driven shaft kinetic friction coefficient (N-m/(rad/s))

### Programming the Clutch Schedule Logic

For this and the following sections, switch the default programmed Clutch Control subsystem to the manually controlled configuration. See “Replacing Programmed with Manually Controlled Clutch Pressures” on page 2-39.

From the main model, open the Clutch Control subsystem. The Clutch Schedule Logic block provides the CR-CR 4-Speed clutch schedule as a truth table for the four forward gears. Each row represents a different gear setting. You select a particular row for output by inputting a set of 1s and 0s that specify the row value as a binary number.

### CR-CR 4-Speed Clutch Schedule Logic

Gear Setting	Truth Table Row	Truth Table Value
1	$00_2 = 0$	1 0 0 1 0
2	$01_2 = 1$	1 0 1 0 0
3	$10_2 = 2$	1 1 0 0 0
4	$11_2 = 3$	0 1 1 0 0

In the order of the CR-CR Clutches—A, B, C, and D, respectively—the sequence of 1s and 0s indicates which clutches are locked (1) and which are free (0). These Boolean values are then converted into normalized clutch pressure signals. The fifth value in each row represents the disengaged reverse gear Clutch R.

### Programming the Reverse Gear

By default, the Forward/Reverse Switch is set to the up position, placing the transmission in forward motion. If you want to engage the reverse gear, set the switch to the down position.

Open the corresponding Reverse block to see the reverse gear clutch schedule as a truth table.

### CR-CR Reverse Gear Clutch Schedule Logic

Gear Setting	Truth Table Value
Reverse	0 0 0 1 1

### Running the CR-CR Transmission Model – Changing Gears

You are now ready to run the model.

- 1 Open the Scopes subsystem, then the individual Scope blocks. Close the Scopes subsystem.  
  
With the Scopes, you can observe the angular velocities of the driving and driven shafts, and the input pressures of the four clutches.
- 2 Open the Clutch Control subsystem, which should be set to manual control. Ensure that the Forward/Reverse Switch is set to up and the Neutral Switch is set to down.  
  
Also ensure that the simulation time is `inf`.
- 3 Start the model. You can change the forward gear settings by changing the Bit1 and Bit2 Switch blocks and moving through truth table entries corresponding to each setting, as summarized in the table, CR-CR 4-Speed Clutch Schedule Logic.

Switching from one gear setting to another unlocks some clutches and locks others, but always leaves two clutches locked. As you change between gear settings, the transmission transfers motion and torque at different ratios. You can disengage the CR-CR transmission completely and engage the Brake by setting the Neutral Switch to up. If you brake, the driven shaft velocity immediately drops to 0. The braking here works the same way as in the previous examples.

You can put the CR-CR transmission into reverse by keeping the Neutral Switch set to down and by setting the Forward/Reverse Switch to down. As with a real transmission, it is best to transition the transmission model through neutral and bring the driven shaft to a rest before putting the transmission into reverse gear.

# Complete Vehicle Model

**In this section...**

“About the Complete Vehicle Model” on page 2-43

“Model the Engine” on page 2-44

“Model the Transmission” on page 2-46

“Couple the Engine to the Transmission” on page 2-46

“Model the Wheels, Tires, and Road” on page 2-47

“Control the Clutches” on page 2-49

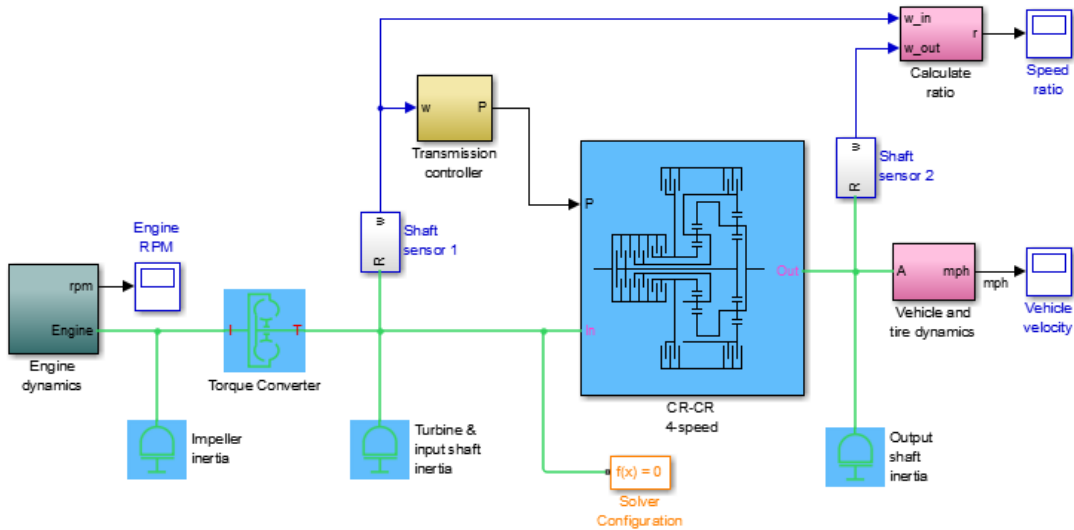
“Run the Model” on page 2-52

## About the Complete Vehicle Model

The full car drivetrain simulation of the `sdl_vehicle` example encompasses all the basic methods of driveline modeling and many key Simscape Driveline features. It includes engine and transmission models and a model of the drivetrain-wheel-road coupling. The engine and transmission are coupled with a torque converter. Programmed clutch control steps the transmission through four gears during the simulation. The clutch pressure signals are smooth and more realistic than the sharp clutch pressure signals in the simpler drivetrain examples. This section describes these features, subsystems, and their relationship and purposes, leading you to actual simulation.

### Understanding the Model's Global Structure

Open the example. The model pre-load function defines a set of workspace variables in MATLAB used by some of the blocks. Note the major systems of this car model.



### Complete Vehicle Model


The main driveline subsystems are:

- Engine
- Transmission
- Transmission controller
- Vehicle and tires

The largest subsystem is the CR-CR 4-speed transmission. While the engine is idling initially at a nonzero speed, the transmission output and the vehicle as a whole are initially not moving.

### Model the Engine

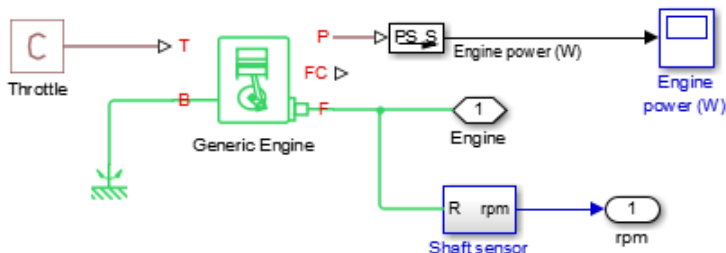
Simscape Driveline software is primarily devoted to modeling the rotational dynamics of drivelines, accepting rotational power from any source that can be modeled in Simulink and converted to a connection line transferring torque. In most applications, your modeled driveline power and torque sources represent engines and motors. For the purposes of system modeling, an engine or motor specifies an output torque as a function

of driveline speed. However you specify the behavior of the engine or motor, its Simscape Driveline output is a connector port  transferring torque to the rest of the system.

### Using an Engine Block from Vehicle Components

The Engines library contains blocks representing simple engine models. You control these engine models with an input physical signal for the throttle. The heart of the engine model is a function that specifies the maximum engine torque possible for each engine speed. The throttle signal controls how much torque, from this maximum possible, that the engine can deliver. The maximum possible torque itself is a function of the engine speed at any instant.

The `sdl_vehicle` example uses a Generic Engine block, configured as spark-ignition type. The block properties specified in its dialog box include the engine's maximum power, its speed at maximum power, and its maximum possible speed. The throttle signal is a physical constant. Open these blocks to view these settings and the throttle profile. The throttle signal is programmed to produce a realistic acceleration profile and to be consistent with the gear shifting sequence described in “Control the Clutches” on page 2-49. The engine torque and motion are modeled relative to the rotational ground, which is taken as the engine's base reference and the starting point of the driveline, or mechanical rotational, connections in this model.



### Engine Dynamics Subsystem

Learn more about the Engine block models from their block reference pages.

### Alternative and Advanced Methods for Modeling Engines

The engine models of the Engines library are simple. You can create your own, more complex, engine models by elaborating on the basic pattern of engine speed determining engine torque output. The complete engine model involves a feedback loop because the

output torque, once connected to the external load, determines how fast the output driveshaft spins. The engine model then uses this output speed to set the maximum possible torque.

Several important engine features to consider in a more complete model are:

- Distinguishing steady-state behavior from engine start-up, when the engine speed-engine torque function has not yet reached its maximum possible envelope
- Details of mechanical power production, such as air-fuel compression and combustion
- Additional controls beyond what can be represented by a single throttle signal

### Model the Transmission

The CR-CR 4-speed transmission subsystem in the `sdl_vehicle` model is similar to other examples with the same transmission. The clutch and planetary gear properties are set in the blocks with workspace variables.

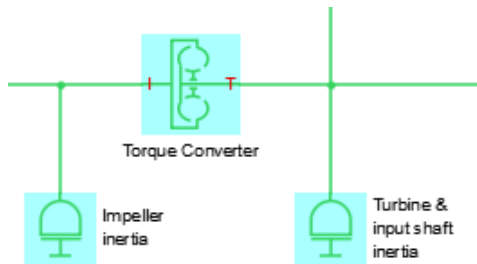
Workspace Variable	Description
<code>eff_tor_rad</code>	Clutch: effective torque radius (m)
<code>num_fric_surf</code>	Clutch: number of friction surfaces in contact
<code>engagement_area</code>	Clutch: friction surface area in contact (m <sup>2</sup> )
<code>fric_coeff</code>	Clutch: kinetic friction coefficient of surfaces in contact
<code>peak_normal</code>	Clutch: static (locking) friction coefficient of surfaces in contact
<code>velTol</code>	Clutch: clutch velocity locking tolerance (rad/s)
<code>pressThresh</code>	Clutch: Normalized pressure threshold
<code>p0</code>	Clutch: Physical pressure normalization (Pa)

For more about gears, clutches, and transmissions, see the [Disk Friction Clutch](#) block reference page.

### Couple the Engine to the Transmission

The `sdl_vehicle` model couples the engine and the transmission through a torque converter subsystem.





### Torque Converter Stage

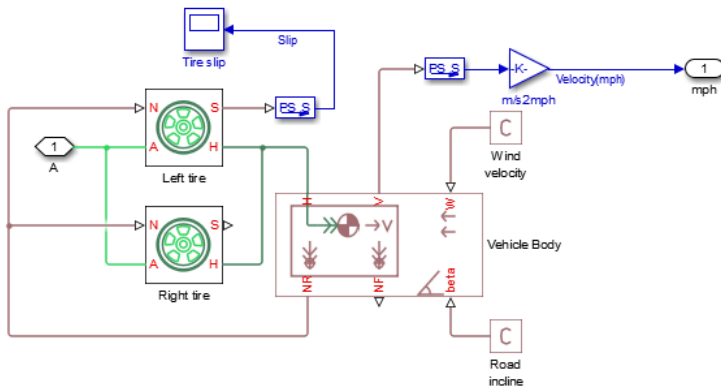
Like clutch, a torque converter couples two independent driveline axes in such a way as to transfer angular motion and torque from an input to an output shaft. However, unlike a clutch, a torque converter never locks and the output shaft never exactly reaches the speed of the input. (The torque converter transfers motion by hydrodynamic viscosity, not by surface friction.) Thus a torque converter does not step through discrete stages and avoids the motion discontinuities inherent in friction clutches.

To mimic engine idling at the start of the simulation, the initial condition of the Impeller inertia is a nonzero angular velocity. The initial condition of the Turbine & input shaft inertia is zero speed.

For more details about these blocks, see the [Torque Converter](#) and [Inertia](#) block reference pages.

### Model the Wheels, Tires, and Road

The CR-CR 4-speed transmission feeds its output torque to the final drive subsystem, Vehicle and tire dynamics. This subsystem represents the vehicle inertia (the load on the transmission), the wheels, and the wheel contact with the road. The dynamics models only the rear wheels as driven by the transmission.



### Final Drive Subsystem: Vehicle Load, Wheels, and Road Coupling

The subsystem has two major areas.

#### Modeling the Tires

On the left of the figure are the two Tires, which accept the driveline torque and rotation from the transmission at their wheel axle rotational ports (A). Given a normal or vertical load (N), this torque and rotation are converted to a thrust force and translation at the wheel hub translational ports (H).

The tires rotate nonideally, developing slip as they generate traction and react against the road surface. The tire slip of the left tire is reported as a physical signal and converted to Simulink for use with the Tire slip scope.

#### Modeling the Vehicle Body and Load

The driveline connection line sequence of the model ends with the **Vehicle Body** block, which specifies the vehicle geometry, mass, aerodynamic drag, and initial velocity (zero). This block generates the normal forces that the Tire blocks accept as vertical loads. Vehicle Body accepts the developed thrust force and motion at its horizontal motion translational port (H). The vehicle body model also requires a wind velocity (W) and a road incline (beta), both provided by physical constants.

The rear wheel vertical load force (NR) is reported back to the Tire blocks. The forward wheel vertical load (NF) is not used.

The vehicle's forward velocity ( $V$ ) is converted and reported, through the subsystem output, to the Vehicle velocity scope.

### **Alternative Differential, Wheel, Road, and Braking Models**

The `sdl_vehicle` example models only the rear wheels, the rear tires, and the vehicle body, without the more realistic drivetrain components of differential gears and brakes. The `sdl_4wd_dynamics` example illustrates how to model a vehicle with four wheels, as well as front and rear differential gears.

You can create and add a brake model built around a clutch. See “Brake Motion with Clutches” on page 2-28 and “Model a Two-Speed Transmission with Braking” on page 2-32.

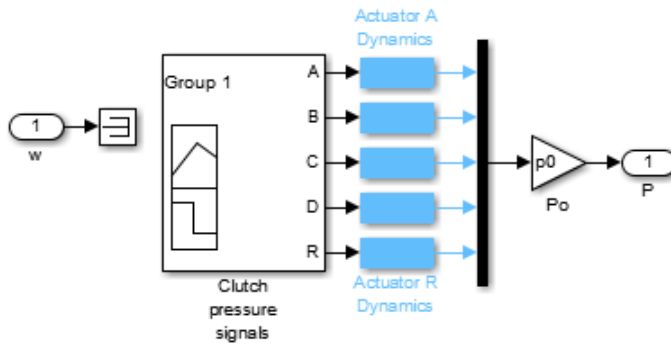
## **Control the Clutches**

Return to the main model window of `sdl_vehicle`. To simulate car motion, the vehicle model requires control signals. One of these signals controls the throttle, as described in “Model the Engine” on page 2-44. The other signals control the clutches. “Run the Model” on page 2-52 presents the full interplay of these control signals and how they determine the simulation results.

### **Programming the Transmission Clutches**

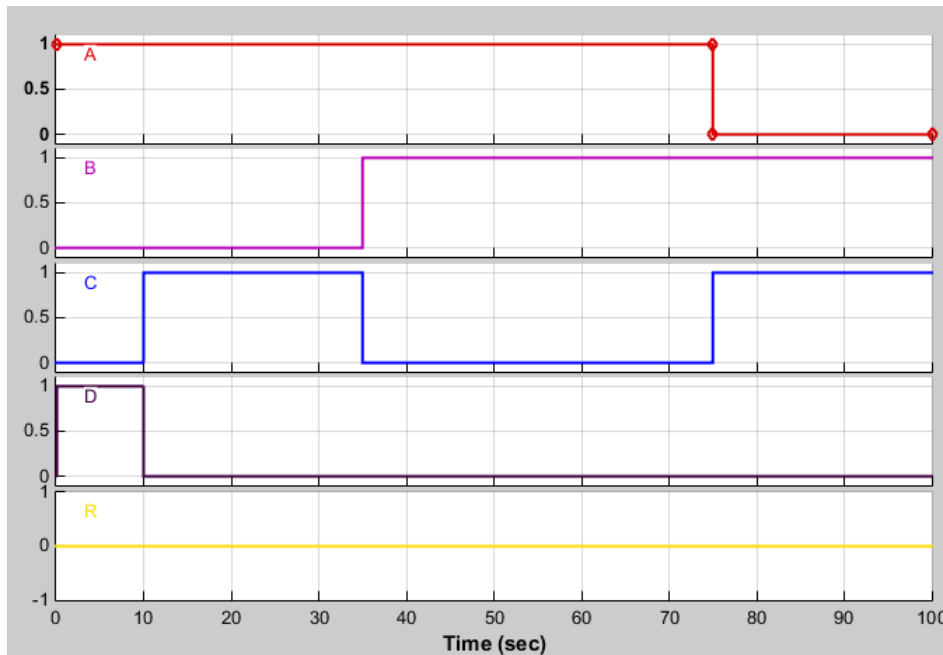
The Transmission controller subsystem controls the five clutches of the CR-CR 4-Speed transmission subsystem.

- 1 Open the Transmission controller. The Signal Builder block, called Clutch pressure signals, contributes five individual signals to lock or unlock the four forward clutches of the CR-CR transmission, and to keep the reverse clutch unlocked.



### Master Transmission Clutch Control

- 2 Close the Transmission controller subsystem.
- 3 Open the Clutch pressure signals block.



### Programmed Clutch Pressure Signals

While the reverse clutch (R) remains unlocked for the entire simulation, the four forward clutches (A, B, C, D) are put through a locking and unlocking sequence that produces a fixed gear-changing sequence for the transmission as a whole: first gear, second gear, third gear, and fourth gear, at 0, 10, 35, and 75 seconds, respectively, of simulation time.

For more details about this transmission and its clutch schedule, see “Model a CR-CR 4-Speed Transmission Driveline with Braking” on page 2-38.

- 4 Close the Clutch pressure signals block.

### Shaping Clutch Pressure Signals

To add realism to the clutch control signals, these signals are filtered through Transfer Fcn blocks (Actuator Dynamics) that smooth their rise and fall, instead of the sharp steps of the original signals.

In the Actuator Dynamics blocks, the characteristic rise/fall time of the transfer functions is set by the workspace variable `clutchRise`, with units of seconds. If  $s_0 = 1/\text{clutchRise}$ , the transfer functions have the form  $s_0/(s+s_0)$ .

### Run the Model

Simulate the car. The model is configured to simulate for 150 seconds.

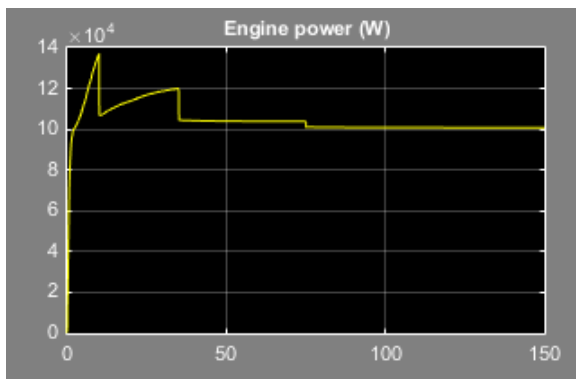
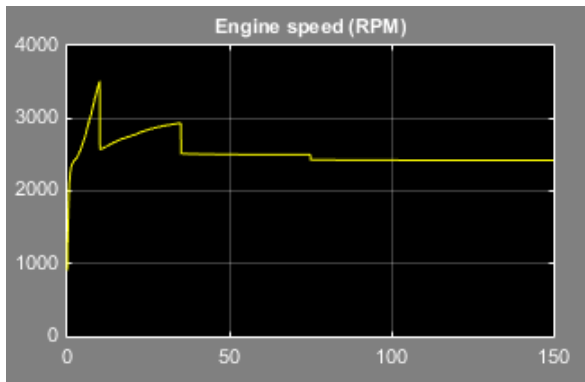
- 1 After closing all subsystems, open the Vehicle velocity, Speed ratio, and Engine RPM scopes.
- 2 Open the Engine dynamics and the Vehicle and tire dynamics subsystems. Open the Engine power and Tire slip scopes. Close the subsystems.
- 3 Review the simulation sequence before starting the model.

Time Ranges	CR-CR Gear Settings
0 – 10	1
10 – 35	2
35 – 75	3
75 – 150	4

- 4 Start the simulation, then review the scope outputs.

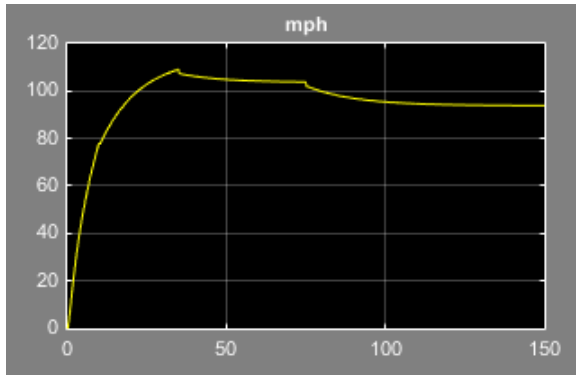
### Engine Speed and Power

The Engine RPM scope shows the engine speed in revolutions per minute (rpm), as well as the engine output power delivered to the Torque Converter, in watts (W). When the transmission shifts to second gear at 10 seconds, the engine reaches its maximum speed and power.



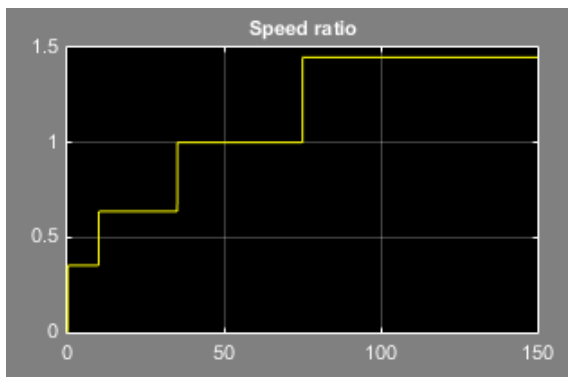
## Vehicle Speed

The Vehicle Velocity scope displays the vehicle's linear velocity in miles per hour (mph).



### Drive Ratio

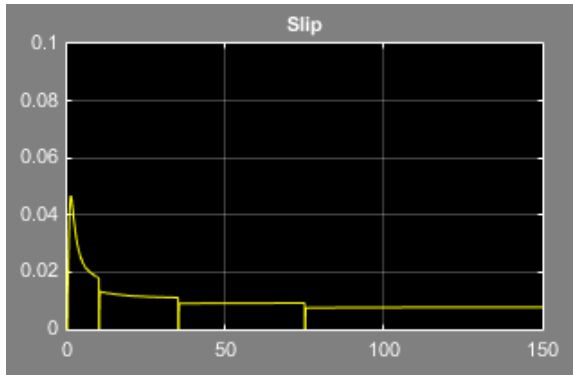
The Speed ratio scope measures the effective gear ratio of the CR-CR 4-speed transmission by computing the ratio of the output shaft to the input shaft angular velocities, respectively. (This ratio is the reciprocal of the drive ratio.) As the transmission shifts through each gear from 1 to 4, its speed ratio goes up, and the drive ratio goes down.





## Tire Slip

The Tire slip scope displays the tire slip, in percent, of the rear tires. As the transmission steps into higher gears, the speed ratio rises. The drive ratio falls, and the tire slip decreases. The tire motion more closely approaches ideal (nonslipping) motion at higher speeds and lower drive ratios.





# Modeling Driveline Components

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These sections introduce you to modeling specialized driveline components in the Simscape Driveline environment. Using predefined blocks from the Simscape Foundation and Simscape Driveline libraries and constructing custom components of your own are both emphasized.

- “Specialized and Customized Driveline Components” on page 3-2
- “Effective Inertias and Driveshafts” on page 3-4
- “Specialized Gears” on page 3-7
- “Specialized Clutches” on page 3-11
- “Rotational-Translational Couplings” on page 3-19
- “Modeling Transmissions” on page 3-21
- “CR-CR 4-Speed Transmission” on page 3-25
- “Lepelletier 6-Speed Transmission” on page 3-29
- “Lepelletier 7-Speed Transmission” on page 3-34
- “Ravigneaux 4-Speed Transmission” on page 3-39
- “8-Speed Transmission” on page 3-43
- “9-Speed Transmission” on page 3-47

## Specialized and Customized Driveline Components

### In this section...

“Optimal Physical Modeling in the Simscape Environment” on page 3-2

“Reasons for Specialized Driveline Components” on page 3-2

“Greater Model Fidelity and Performance” on page 3-3

### Optimal Physical Modeling in the Simscape Environment

Within the Simulink environment, you follow best practice if you model driveline systems by representing as much of the physical system as possible with Simscape Driveline and Simscape components. Major advantages include these features that make it easier to create accurate simulations of physical systems:

- Physical ports and connection lines supporting physical units
- Data logging
- Specialized solvers
- Consistent treatment of differential and algebraic constraint equations
- Customization with Simscape Foundation blocks and Simscape language

For custom block modeling with Simscape language, see “*Custom Components*”.

Reserve Simulink blocks and signals for nonphysical aspects of modeling, such as nonphysical signals, algorithmic control, and model-level input/output tasks.

### Reasons for Specialized Driveline Components

Simscape Driveline and Simscape physical connections help you create model architectures with clear physical component boundaries. You can then increase the fidelity of the model overall, or make only certain components more accurate representations of the system.

In driveline modeling, there are several reasons for making a model more complex and accurate.

#### Complex Component Geometries

Driveline models abstract the motion of three-dimensional mechanical systems constrained to move in one dimension. Some driveline components require extra

specification to capture underlying two- and three-dimensional geometry. An example in the Simscape Driveline library is the `Differential` gear.

### **Internal Compliance Dynamics**

Many standard Simscape Driveline components allow you to enable or disable modeling of internal dynamics. For example, `Generic Engine` allows you to represent an engine with instantaneous response for a simple, idealized model. A more complex and accurate representation is available in `Generic Engine`, if you enable its internal time lag. You can also create your own custom components (with internal compliance dynamics, for example), to whatever degree of fidelity and complexity that you want.

### **Frictional Losses**

Much of complex internal dynamic Simscape Driveline modeling comes from representing the effect of both viscous and Coulomb friction.

- Viscous friction is proportional to the relative velocity of two surfaces in contact.
- Coulomb, or “sliding-sticky,” friction is proportional to the force normal to surfaces in contact. For low relative velocities, Coulomb friction causes surfaces to lock and cease relative motion.

Thus, friction models involve specification of relative geometry and motion, friction coefficients, and normal forces, of surfaces in contact.

Components with internal friction models include gears, clutches, tires, and other couplings, at different levels of optional complexity.

## **Greater Model Fidelity and Performance**

In most cases, greater fidelity of model components results in reduced simulation performance and changes the tradeoff between simulation accuracy and speed. You can adapt your simulation methods to handle greater fidelity, or reduce model fidelity to enhance performance.

For a discussion of how model fidelity and performance are related to simulation settings, see “Adjust Model Fidelity” on page 4-2 in “Driveline Simulation Performance” on page 4-2.

## Effective Inertias and Driveshafts

<b>In this section...</b>
“Model a Variable Inertia” on page 3-4
“Model Driveshafts with Loss” on page 3-6

### Model a Variable Inertia

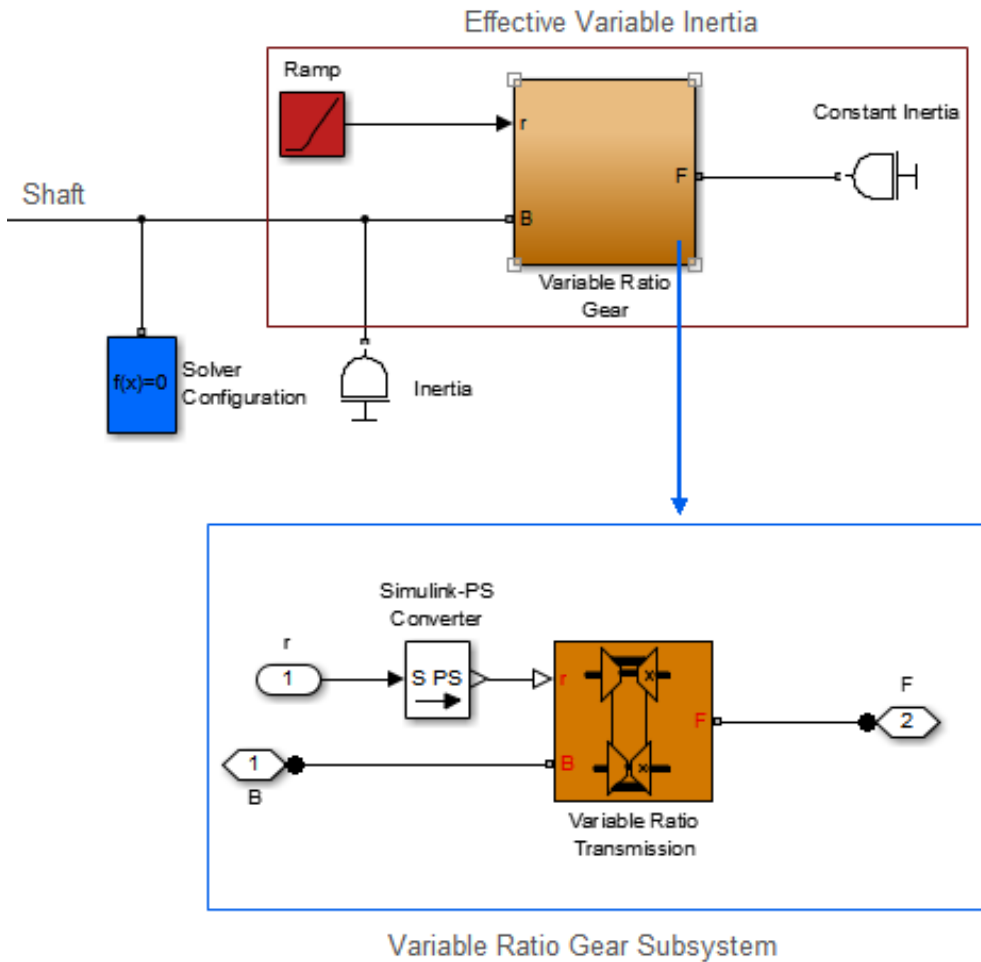
You cannot vary the inertia value of an **Inertia** block during a simulation. However, you can model a time-varying inertia indirectly with a **Variable Ratio Transmission** block. The **Inertia** block interacts with the rest of the system, including any applied torque, only through the gear with the time-varying gear ratio.

- 1 Place a Variable Ratio Transmission between a shaft and an Inertia.
- 2 Connect this constant Inertia to the Transmission base (B) or follower (F) port.
- 3 Vary the gear ratio  $g(t)$  of the Variable Ratio Transmission with an incoming physical signal.

By changing the gear ratio, you change the effective inertia  $I_{\text{eff}}$  on the shaft from the constant Inertia (value  $I$ ).  $I_{\text{eff}}$  is the effective inertia presented to the rest of the system as torque is applied, through the variable ratio gearbox, on the Inertia.

- If the B port is connected to the constant Inertia,  $I_{\text{eff}} = I \cdot [g(t)]^2$
- If the F port is connected to the constant Inertia,  $I_{\text{eff}} = I / [g(t)]^2$

In this diagram, the Variable Ratio Transmission is contained within the Variable Ratio Gear subsystem.



**Effective Variable Inertia with a Variable Ratio Gearbox**

### **Model Driveshafts with Loss**

Realistic driveshafts experience damping from viscous friction, which is proportional to the driveshaft angular velocity. You can model such damping with the **Rotational Damper** and, if necessary, build complex damping subsystems from this block.



## Specialized Gears

### In this section...

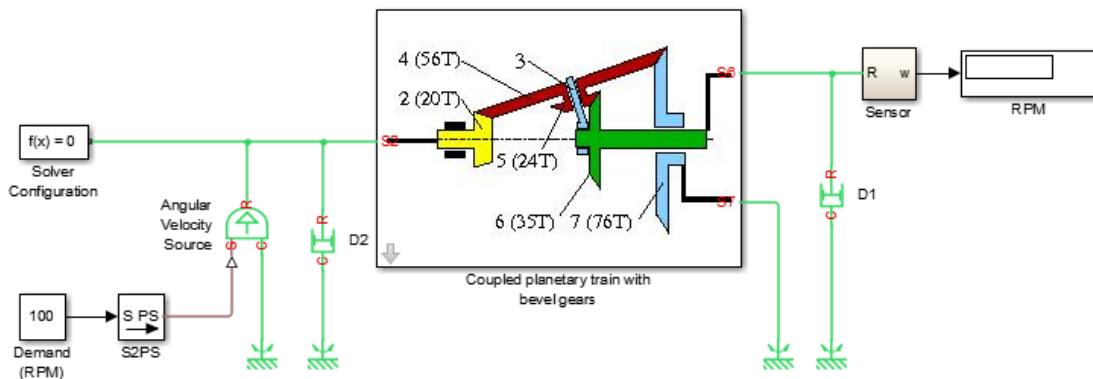
“Custom Planetary Gear Model” on page 3-7

“Model Gears with Losses” on page 3-8

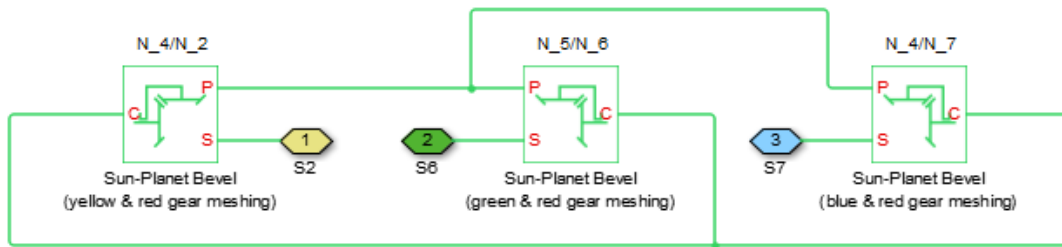
“Constant and Load-Dependent Gear Efficiencies” on page 3-9

### Custom Planetary Gear Model

While the Simscape Driveline library contains a **Planetary Gear**, you can create your own custom planetary gear using the **Planetary Subcomponents** sublibrary. The `sdl_custom_planetary_gear` example model combines three **Sun-Planet Bevel** subgears into a masked subsystem to model a coupled planetary gear train. The model uses an **Ideal Angular Velocity Source** to place a fixed velocity demand on the gearbox input, while damping the system on both the input and output driveshafts with **Rotational Dampers**.



### Custom Planetary Gear System and Subsystem



## Model Gears with Losses

The blocks of the Simscape Driveline Gears Library contain optional built-in models of frictional losses, allowing you to represent nonideal gear couplings. In a nonideal gear pair (1,2), the angular velocity, gear radii, gear teeth constraints, and gear ratio  $g_{12} = r_2/r_1 = \omega_1/\omega_2$  are unchanged. The transferred torque and power are reduced by:

- Coulomb friction between imperfectly meshing teeth surfaces on gears 1 and 2, parameterized by an efficiency  $\eta$ ,  $0 < \eta \leq 1$ . This efficiency depends on the torque load on the teeth. But it is often approximated as constant.
- Viscous coupling of driveshafts with bearings, parameterized by viscous friction coefficients  $\mu$ .

### Constant Efficiency

In the simplest nonideal gear loss model, the efficiency  $\eta_{12}$  of meshing in gear pair (1,2) is constant, independent of load (torque or power transferred).

- The friction loss represented by  $\eta_{12}$  is effectively applied in full only if the transmitted power is greater than the power threshold  $p_{th}$ . Below this value, a hyperbolic tangent function smooths the efficiency factor, lowering the efficiency losses to zero when no power is transmitted.
- For gear sets with a carrier,  $\eta_{12}$  represents the ordinary efficiency, defined when the carrier is not moving.

For gears with different efficiencies for the forward and reverse power flow:

- $ForwardLoss = (1 - \eta_{FB})$ ,  $\eta_{FB}$  is the torque transfer efficiency from the follower shaft to the base shaft.

- $BackwardLoss = (1/\eta_{BF} - 1)$ , where  $\eta_{BF}$  is the torque transfer efficiency from the base shaft to the follower shaft.

The frictional torque is calculated as:

$$T_f = T / 2((ForwardLoss + BackwardLoss)\tanh(4p / p_{th}) + ForwardLoss - BackwardLoss)$$

where:

- $T$  is the transferred torque.
- $p$  is the transferred power.
- $p_{th}$  is the power threshold at the base shaft above which full efficiency losses are in effect.

For certain gear models, such as the **Simple Gear**, efficiency is assumed equal for both the forward and reverse power flow,  $\eta_{BF} = \eta_{FB}$ .

### Load-Dependent Efficiency

Making  $\eta$  dependent on the load is a way to make the loss model more accurate. For an example of load-dependent efficiency, see the **Simple Gear** block reference page.

### Geometry-Dependent Efficiency

Making  $\eta$  dependent on the geometry of gear meshing is another way to make the loss model more accurate. For an example of geometry-dependent efficiency, see the **Leadscrew** block reference page.

### Viscous Friction

On a driveshaft mounted to a gear wheel by lubricated, nonideal bearings, the viscous friction experienced by the axis is controlled by the viscous friction coefficient  $\mu$ . The viscous friction torque on a driveshaft “a” is  $-\mu_a \omega_a$ , where  $\omega_a$  is the angular velocity of the driveshaft with respect to its mounting or carrier (if a carrier is present).

## Constant and Load-Dependent Gear Efficiencies

Here, you revisit the `sdl_simple_transmission` model in “Model a Two-Speed Transmission with Braking” on page 2-32. You reconfigure the **Simple Gears** to model power loss due to nonideal meshing. The effect of viscous bearing losses is ignored.

- 1 Open the `sdl_simple_transmission` model and simulate to check the ideal gear behavior.

- 2 Open the Simple Gear 5:1 and Simple Gear 2:1 blocks. Under **Meshing Losses**, in the **Friction model** drop-down list, choose **Constant efficiency** for both. Enter efficiencies less than 1, but greater than 0. For example, for the 5:1 gear, enter 0.7; and for the 2:1 gear, enter 0.95.
- 3 Leave the other settings as they are, including zero viscosity. Close the blocks.
- 4 Restart the model. The driveline runs at a lower efficiency and slightly smaller angular velocities, because of the power losses. If you enter different efficiency factors for the two gears, the effect of the loss is different if you switch between gears.

Experiment with load-dependent efficiency. In the **Friction model** drop-down menu, choose **Load-dependent efficiency** instead. In that case, you need more efficiency model details to specify.

## Specialized Clutches

### In this section...

“Clutches, Clutch-Like Elements, and Coulomb Friction” on page 3-11

“Model Clutches with Viscous Friction Loss” on page 3-12

“Model Realistic Clutch Pressure Signals” on page 3-16

“Automatic Transmission with a Dual Clutch” on page 3-16

### Clutches, Clutch-Like Elements, and Coulomb Friction

Coulomb friction acts along the plane of contact between two solid surfaces, in opposition to their actual or potential relative motion, and in proportion to the normal force pushing the surfaces together. It encompasses both kinetic friction, applied when the surfaces are in relative motion, and static friction, applied when they are locked together. Coulomb friction is the basis for clutches and clutch-like elements that rely on normal forces to keep surfaces in contact. When the relative speed of the surfaces becomes small enough, these elements lock and move together.

Realistic friction models often include viscous friction. This type of frictional force or torque is proportional to the relative translational or rotational velocity of the two surfaces in contact.

The **Clutches** library contains models of standard clutches that couple two rotating driveline axes. The **Brakes & Drives** and **Couplings & Drives** libraries provide blocks to construct clutch-like elements of your own, including detents, brakes, and specialized clutches. These clutch-like elements apply Coulomb friction forces or torques between pairs of translating or rotating axes in loaded contact. They also allow inclusion of viscous friction. Once engaged, clutches and brakes act to decelerate the relative motion of surfaces in contact and can lock the surfaces together under certain conditions.

Clutches and clutch-like elements have a dual role in a driveline model. When engaged but not locked, they act as *dynamic elements*, generating torques and forces between driveline axes in relative motion. When locked, they act as *conditional or dynamic constraints*, locking driveline axes to move together. Such constraints are conditional, because they can unlock, unlike gears.

For more information on clutches and dynamic constraints, see “Driveline Degrees of Freedom” on page 4-10 and “Driveline States — Effect of Clutches” on page 4-24.

## Model Clutches with Viscous Friction Loss

The main loss in a clutch system coupling two driveshafts comes from viscous friction at the two shaft bearings. Consider the `sdl_simple_clutch` model, presented in “Engage and Disengage Gears with Clutches” on page 2-23. Here you add a kinetic friction torque proportional to the angular velocity on both sides of the clutch (viscous friction). The Simscape Foundation library provides a **Rotational Damper** block that represents such a damper. The angular motion of the driveshafts is relative to another component. Here the angular velocities of the shafts are measured relative to rotational ground, represented by **Mechanical Rotational Reference**. You can make a friction subsystem that applies such a torque to any driveline axis connected to it. You can copy the subsystem and modify the existing clutch model by connecting the two copies on either side of the clutch.

---

**Note:** The velocity used in this damping is the absolute velocity of a single shaft relative to rest. If you had *two* rotating driveline shafts and wanted to exert a relative damping between them as a function of their *relative* velocities, use the same Rotational Damper block connected between the two axes.

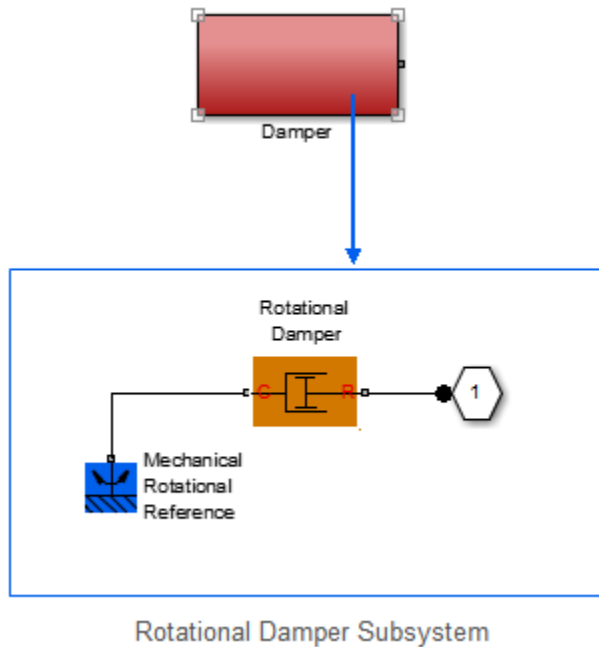
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### Creating a Torque Damping Subsystem

The viscous friction torque is  $\tau_{\text{fric}} = -\mu\omega$ , where  $\mu$  is the viscous friction coefficient. To implement this torque:

- 1 From the Simscape library, copy **Mechanical Rotational Reference**, **Rotational Damper**, and **Connection Port** into your model window.
- 2 Connect the **Mechanical Rotational Reference** to the case (C) port of the **Rotational Damper** and the rod (R) port of the **Rotational Damper** to the **Connection Port**.
- 3 Open the **Rotational Damper**. For **Damping coefficient**, enter **0.3**. Leave the default units. Close the dialog box.
- 4 Select the whole connected three-block set, and create a subsystem. Call it **Damper**.

Create a second copy of **Damper**.

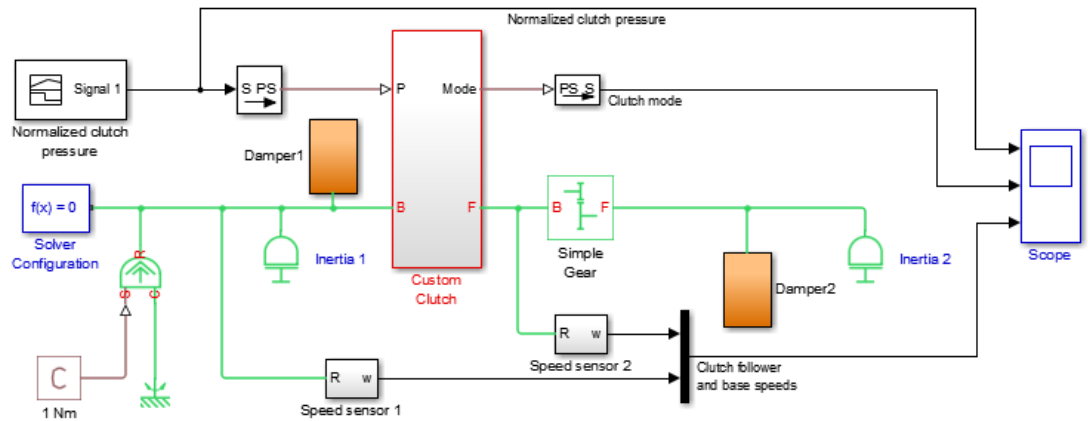


### Rotational Damping Subsystem

#### Connecting and Simulating the Damped Clutch System

Complete and run the model.

- 1 Connect the two Damper subsystems to the driveline of your previous clutch model, as shown.

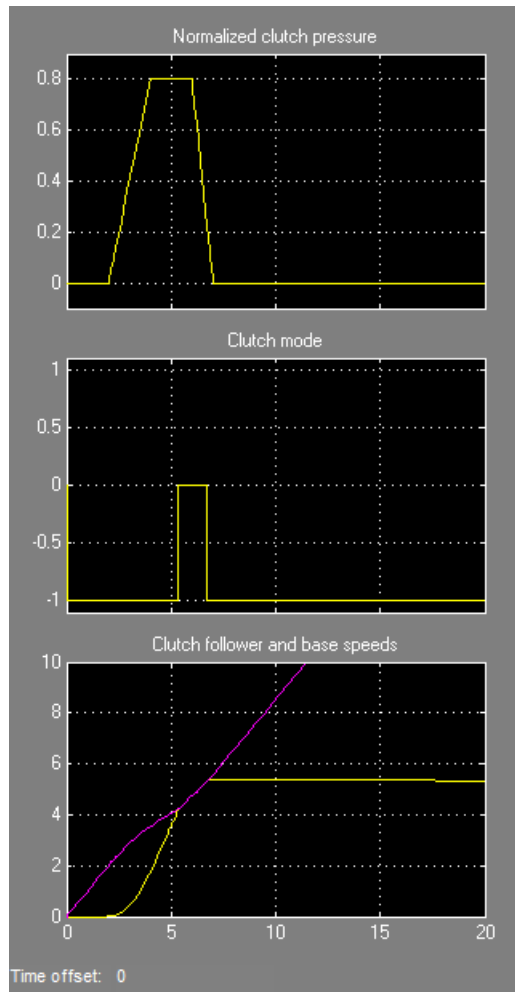


#### Damped Simple Clutch Model

- 2 Change the simulation time to 20 seconds. Open the Scope blocks and click **Start**.

Readjust the horizontal axes of the Scope with **Autoscale** to see the full plots. The clutch pressure and external torques are applied as before. The shaft rotations are now different because of the damping.





As before, Inertia2 begins to spin when the clutch starts to engage at 2 seconds. After the clutch locks at 4 seconds, the body continues to accelerate, at a slower rate than it did without damping. At about 6.7 seconds, the clutch begins to disengage and completely disengages at 7 seconds. Subject to friction, Inertia2 now starts to slow down, unlike in the friction-free case. Once the external torque is removed, its angular velocity drops exponentially with time.

The behavior of Inertia1 is more complex. It begins to spin up, at a lower rate than before, because of the damping. Between 2 and 7 seconds, Inertia1 shares the external torque with Inertia2 via the Clutch and the Simple Gear. After 7 seconds, the external torque applies to Inertia1 alone. It continues to accelerate, at an ever-slowng rate, because of the damping. If you let the simulation run without stopping, Inertia will approach its terminal angular velocity, a state where the frictional torque exactly balances the externally applied torque. This terminal velocity is  $\omega_{\text{term}} = \tau_{\text{ext}}/\mu$  or  $1/0.3 = 3.3333$  radians/second. The third Scope plot approaches this terminal value.

## Model Realistic Clutch Pressure Signals

The most critical addition that you can make to clutch models for greater realism is to change the clutch pressure signals from step functions (0 to 1, or 1 to 0) to signals with a smooth rise and fall. This greater realism results in a more complex model. At any simulation time, it is critical for your model to determine transmission motion by locking exactly the correct number of clutches. (If all clutches are unlocked, the transmission is in neutral.) Changing a transmission's gear settings while maintaining this requirement is one of the central problems of transmission design.

Such transmission and vehicle models as `sdl_crcr` and `sdl_vehicle` switch gear settings without placing their transmissions in neutral. Controlling an actual manual transmission requires moving the transmission out of gear and into neutral, picking a new gear setting, and then putting the transmission into the new gear.

In the `sdl_crcr` example, with manual transmission control, you can mimic these steps by turning on the Neutral Switch, changing the gear setting, then turning off slipping the Neutral Switch.

In a programmed transmission control model, you can filter clutch pressures with Transfer Fcn blocks, shaping the pressure signals from sharp steps to smooth rises or falls.

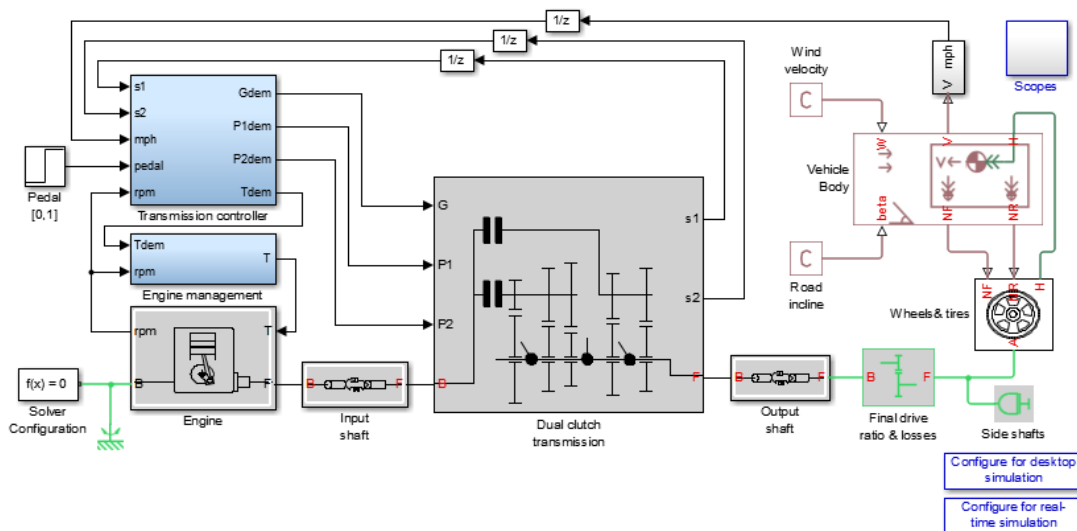
## Automatic Transmission with a Dual Clutch

The `sdl_dual_clutch` example model illustrates important points about both physical and control design modeling using the Simscape and Simscape Driveline environment and libraries.

The model represents an automatic transmission with two clutches. In an automatic transmission, the decision of when to change gear ratio and what the next gear ratio

will be is made by an engine management subsystem. The pedal deflection imposed by a vehicle driver is converted into a demanded engine torque. The torque demanded and the current forward vehicle speed together determine which gear ratio the transmission will switch to before it actually switches (gear preselection). By gradually lowering the clutch pressure, the transmission control system smoothly unlocks and disengages the clutch configuration for the current gear ratio. At the same time, the control system gradually raises the clutch pressures to achieve the new gear ratio by engaging and locking the new clutch configuration.

- The physical components of the transmission, from the engine, gears, and clutches, to the vehicle body and tire, are modeled using Simscape Driveline blocks, with physical ports and connections.
- The algorithmic control of the transmission, including the gear-switching and transmission control, is modeled using normal Simulink blocks, with signal ports and lines, as well as enabled subsystems.



## Dual-Clutch Model with Gear Preselection

### Predefined Simulation Options

The model is also set up to switch between two common simulation configurations.

- If you double-click the subsystem icon for desktop simulation, you configure the model to simulate with a variable-step global solver, without fixed-cost or fixed-step local solver options.
- If you double-click the subsystem icon for real-time simulation, you configure the model to simulate with a discrete-time, fixed-step global solver, as well as a fixed-cost, fixed-step local solver.

You can directly adjust all the solver options by opening the model Configuration Parameters and the network Solver Configuration dialog boxes.

## Rotational-Translational Couplings

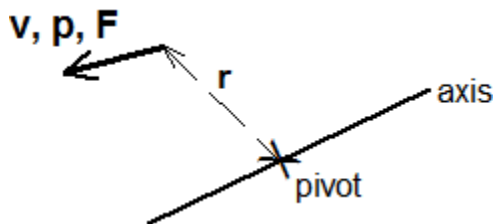
### In this section...

“Convert Between Rotational and Translation Motion” on page 3-19

“Use Simscape and Simscape Driveline Elements to Couple Rotation and Translation” on page 3-19

### Convert Between Rotational and Translation Motion

In general, mechanical systems mix rotational and translational motion. Rotational dynamics and motion about an axis couples to translational dynamics and motion (velocity  $v$ , momentum  $p$ , force  $F$ ) at some distance (moment arm  $r$ ) from the rotational pivot through a constraint that captures only motion normal to the moment arm.



While most driveline components involve rotational motion around fixed axes, certain key components transform translational and rotational motions from one to the other. Such components map motion along lines and motion around circles to one another.

The rack-and-pinion is an example of a mixed-motion gear constraint. Tires and propellers use contact friction to change driven rotational motion into forward or backward linear motion.

### Use Simscape and Simscape Driveline Elements to Couple Rotation and Translation

Simscape and Simscape Driveline components that couple rotational and translational motion have mixed mechanical conserving ports of both rotational and translational type. Such blocks include wheels and tires, as well as certain gears:

- Leadscrew

- Rack & Pinion
- Tire (Magic Formula)
- Wheel and Axle

For an example of rotational-translational coupling with Tire (Magic Formula), see the model in “Complete Vehicle Model” on page 2-43.

# Modeling Transmissions

**In this section...**

“Transmission Templates” on page 3-21

“Transmission Ports” on page 3-21

“Gear Input Signal” on page 3-21

“Initial States” on page 3-22

“Clutch Control” on page 3-23

“Inertias and Friction Losses” on page 3-23

“Real-Time Simulation” on page 3-24

## Transmission Templates

The Transmissions library provides subsystem templates for modeling geared transmission systems with four to nine speed settings. The templates use Simscape Driveline and Simscape blocks to represent the transmission components—their gears, clutches, and brakes. An embedded Simulink subsystem defines the clutch schedule.

Use the templates as starting points and examples for your own transmission models. The template blocks are not library-linked, so you can modify them to suit your needs. Add, remove, or reconnect blocks to change the transmission structure. Modify block parameters to capture transmission losses due to gear meshing or viscous damping.

## Transmission Ports

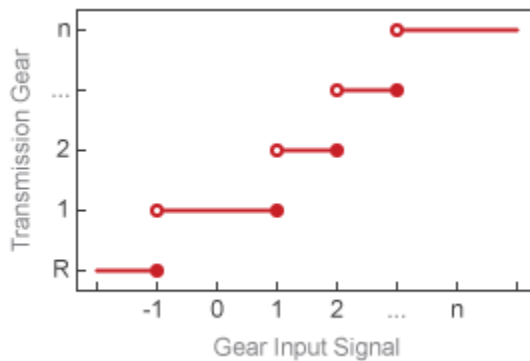
The transmission template blocks each have three ports. Two ports, labeled B and F, are rotational conserving ports. They represent, interchangeably, the input and output shafts. One port, labeled Gear, is a Simulink input port. Use this port to shift gears during simulation.

## Gear Input Signal

The input signal to the Gear port sets the transmission gear according to the expression:

$$\text{Gear Setting} = \begin{cases} \text{Rev,} & \text{if Gear} \leq -1 \\ 1^{\text{st}}, & \text{if } -1 < \text{Gear} \leq +1 \\ 2^{\text{nd}}, & \text{if } +1 < \text{Gear} \leq +2 \\ \dots, & \dots \\ n^{\text{th}} & \text{if } (n-1) < \text{Gear} \leq n \end{cases} .$$

The figure shows the correspondence between the transmission gear and the Gear input signal.



## Initial States

The transmission templates are configured to begin simulation in first gear. To change the default initial gear, you must set the clutch and brake initial states to the values shown in the transmission clutch schedules. You change the initial states in the **Initial Conditions** tab of the block dialog boxes.

Consider the Lepelletier 6-Speed Transmission template. The transmission clutch schedule shows the clutch and brake initial states for reverse gear to be [1 0 0 1 0] in the order A-E. To begin simulation in reverse gear, you must then set the initial states in the block dialog boxes as follows:

- Clutch A locked
- Clutch B unlocked
- Clutche C unlocked



- Clutch D locked
- Clutch E unlocked

The Gear input signal must agree with the clutch and brake initial states. If the initial states correspond to reverse gear, then the first value in the Gear input signal must also correspond to reverse gear ( $Gear \leq -1$ ). Matching the two in this way helps to avoid inconsistent states known to cause simulation errors.

## Clutch Control

The clutch schedule converts the Gear input signal into clutch and brake input signals. These signals drive the clutches and brakes, causing some to lock and others to unlock in an orchestrated fashion. The resulting configuration determines which gears power flows through—and therefore which gear the transmission is in.

A Gain block scales the input signals to the proper magnitudes for actuating the clutches and brakes. These magnitudes depend on the actuation inputs expected by the Clutch and Brake blocks. The actuation inputs can be:

- Shift linkage displacements in Dog Clutch blocks
- Normal forces in Cone Clutch and Loaded-Contact Rotational Friction blocks
- Plate pressures in Disk Friction Clutch blocks

Transfer Function blocks smooth the otherwise discrete input signals using first-order filters. The smoothing allows the clutch state transitions to occur gradually over short periods of time rather than instantaneously. The transfer function time constants determine the characteristic time periods over which the clutch transitions occur.

## Inertias and Friction Losses

Simscape Inertia blocks represent the inertias of transmission gears. These blocks enhance the accuracy of the model. They also prevent simulation errors due to zero-inertia gear sets disconnected from input and output shafts due to clutch unlocking.

By default, all frictional losses are set to zero. Frictional losses include those due to meshing in gears and viscous damping in gears, clutches, and brakes. To account for frictional losses in your model, you must specify gear efficiencies and friction coefficients in the block dialog boxes.

### Real-Time Simulation

Transmission components such as gears and clutches can slow down simulation by introducing zero-crossing events and complex state-change calculations to your model. To minimize their impact on simulation speed, several blocks provide optional parameterizations suited for real-time simulation. These include:

- **Friction clutch approximation** in dog clutches — Reduces model stiffness due to backlash-induced vibrations.
- **No meshing losses** in gears — Eliminates gear friction calculations and associated zero crossings due to motion reversals.

These block parameterizations are labeled **Suitable for HIL**. Use them if you intend to run any type of real-time simulation, including hardware-in-loop (HIL) and software-in-loop (SIL) simulation. By default, all gear and clutch blocks in the transmission templates are set to use these parameterizations.

### More About

- “CR-CR 4-Speed Transmission” on page 3-25
- “Ravigneaux 4-Speed Transmission” on page 3-39
- “Lepelletier 6-Speed Transmission” on page 3-29
- “Lepelletier 7-Speed Transmission” on page 3-34
- “8-Speed Transmission” on page 3-43
- “9-Speed Transmission” on page 3-47

## CR-CR 4-Speed Transmission

### In this section...

“Transmission Overview” on page 3-25

“Clutch Schedule” on page 3-25

“Power Flow” on page 3-26

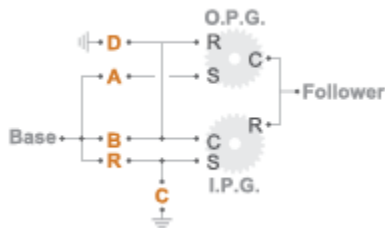
“Drive Ratio” on page 3-27

### Transmission Overview

The CR-CR 4-speed transmission consists of two planetary gear sets (I.P.G. and O.P.G. in the figure) and five disk friction clutches (A–D and R in the figure). The follower shaft connects to the planet gear carrier of O.P.G. and ring gear of I.P.G. Clutches A–B and R determine which gears the base shaft connects to. Clutches C–D act as brakes, grounding various gears of the planetary sets to the transmission housing.

In the figure, labels superposed on a gear silhouette identify the gear components:

- R — Ring gear
- C — Planet gear carrier
- S — Sun gear



### Clutch Schedule

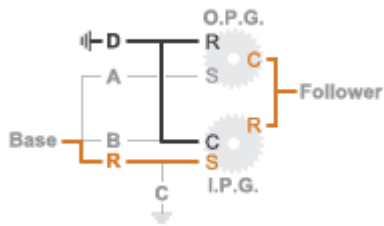
The table shows the clutch schedule of the CR-CR 4-speed transmission. The letters in the header denote the transmission brakes and clutches. A value of 1 denotes a locked state and a value of 0 an unlocked state. The clutch schedule automatically generates

these signals based on the Gear port input signal specified. The signals are then scaled through a Gain block and used as actuation inputs in the clutch blocks.

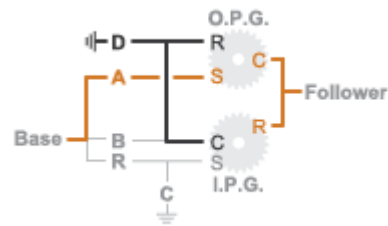
Gear	A	B	C	D	R
R	0	0	0	1	1
1	1	0	0	1	0
2	1	0	1	0	0
3	1	1	0	0	0
4	0	1	1	0	0

### Power Flow

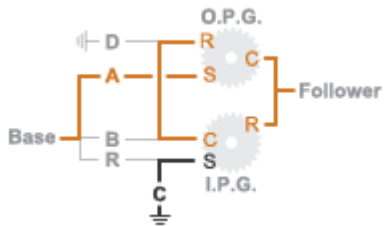
The figures show the power flow paths between input and output shafts for each gear setting. Power flow is shown in orange. Connections to the transmission housing (a mechanical ground) are shown in black.



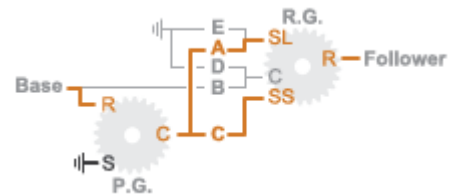
Reverse Gear



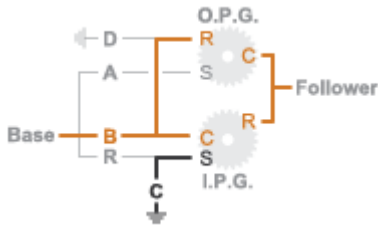
First Gear



Second Gear



Third Gear



### Fourth Gear

### Drive Ratio

The drive ratio between the transmission input and output shafts follows from the elementary gear ratios specified in the gear blocks dialog boxes. The elementary gear ratios are

$$g_1 = \frac{N_{RI}}{N_{SI}},$$

and

$$g_2 = \frac{N_{RO}}{N_{SO}},$$

where:

- $N_{RI}$  is the number of teeth in the planetary ring gear on the input shaft side.
- $N_{SI}$  is the number of teeth in the planetary sun gear on the input shaft side.
- $N_{RO}$  is the number of teeth in the planetary ring gear on the output shaft side.
- $N_{SO}$  is the number of teeth in the planetary sun gear on the output shaft side.

The table shows the drive ratio expressions and their default values for the various transmission gears.

Gear	Drive Ratio	Default Ratio
------	-------------	---------------

R	$-g_1$	-2:1
1	$1 + g_2$	3:1
2	$1 + \frac{g_2}{1 + g_1}$	1.67:1
3	1	1:1
4	$\frac{g_1}{1 + g_1}$	0.67:1

#### More About

- “Ravigneaux 4-Speed Transmission” on page 3-39
- “Lepelletier 6-Speed Transmission” on page 3-29
- “Lepelletier 7-Speed Transmission” on page 3-34
- “8-Speed Transmission” on page 3-43
- “9-Speed Transmission” on page 3-47

## Lepelletier 6-Speed Transmission

### In this section...

“Transmission Overview” on page 3-29

“Clutch Schedule” on page 3-29

“Power Flow” on page 3-30

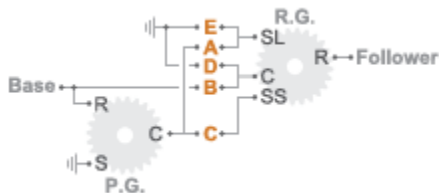
“Drive Ratio” on page 3-31

### Transmission Overview

The Lepelletier 6-speed transmission consists of one planetary gear set (P.G. in the figure), one Ravigneaux gear set (R.G.), and five disk friction clutches (A–E). The transmission base shaft connects to the ring gear of the planetary gear set. The follower shaft connects to the ring gear of the Ravigneaux gear set.

Clutches A–C control the power flow paths between the planetary and Ravigneaux gear sets. Clutches D–E serve as brakes, grounding various gears of the Ravigneaux set to the transmission housing. In the figure, labels imposed on a gear silhouette identify the gear component:

- R — Ring gear
- C — Planet gear carrier
- S — Sun gear
- SL — Large sun gear
- SS — Small sun gear



### Clutch Schedule

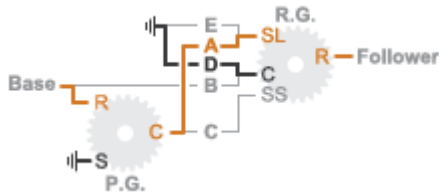
The table shows the clutch schedule of the Lepelletier 6-speed transmission. The letters in the header denote the brakes and clutches. A value of 1 denotes a locked state and a

value of 0 an unlocked state. The clutch schedule automatically generates these signals based on the Gear port input signal specified. The signals are then scaled through a Gain block and used as actuation inputs in the clutch blocks.

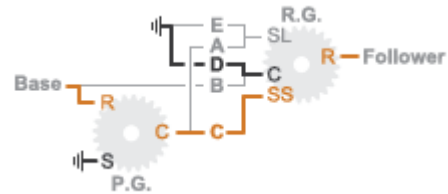
Gear	A	B	C	D	E
R	1	0	0	1	0
1	0	0	1	1	0
2	0	0	1	0	1
3	1	0	1	0	0
4	0	1	1	0	0
5	1	1	0	0	0
6	0	1	0	0	1

### Power Flow

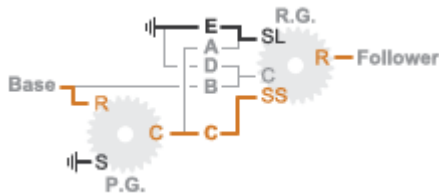
The figures show the power flow paths between the input and output shafts for each gear setting. Power flow is shown in orange. Connections to the transmission housing (a mechanical ground) are shown in black.



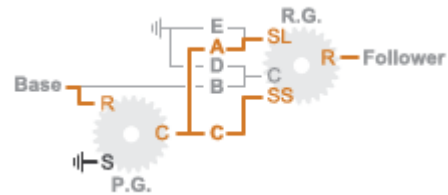
**Reverse Gear**



**First Gear**

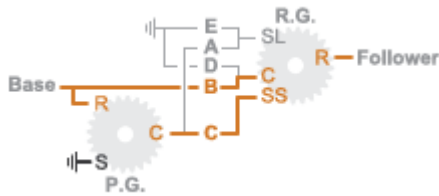


**Second Gear**

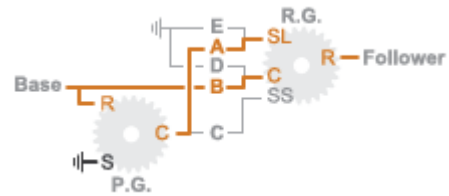


**Third Gear**

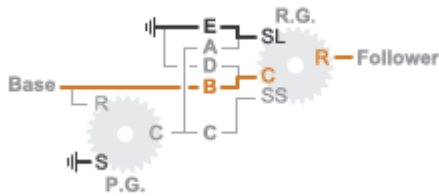




Fourth Gear



Fifth Gear



Sixth Gear

## Drive Ratio

The drive ratio between the transmission input and output shafts follows from the elementary gear ratios specified in the gear block dialog boxes. The elementary gear ratios are

$$g_1 = \frac{N_{PR}}{N_{PS}},$$

$$g_2 = \frac{N_{PR}}{N_{RSL}},$$

and

$$g_3 = \frac{N_{RR}}{N_{RSS}},$$

where:

- $N_{PR}$  is the number of teeth in the planetary ring gear.
- $N_{PS}$  is the number of teeth in the planetary sun gear.
- $N_{RR}$  is the number of teeth in the Ravigneaux ring gear.
- $N_{RSL}$  is the number of teeth in the Ravigneaux large sun gear.
- $N_{RRS}$  is the number of teeth in the Ravigneaux small sun gear.

The table shows the drive ratio expressions and their default values for the various transmission gear settings.

<b>Gear</b>	<b>Drive Ratio</b>	<b>Default Ratio</b>
R	$-\frac{g_2(1+g_1)}{g_1}$	-3.36:1
1	$\frac{g_3(1+g_1)}{g_1}$	4.12:1
2	$\frac{(1+g_1)(g_3+g_2)}{g_1(1+g_2)}$	2.31:1
3	$\frac{1+g_1}{g_1}$	1.50:1
4	$\frac{g_3(1+g_1)}{g_3(1+g_1)-1}$	1.14:1
5	$\frac{g_2}{g_2+1/(1+g_1)}$	0.87:1
6	$\frac{g_2}{1+g_2}$	69:1

### More About

- “CR-CR 4-Speed Transmission” on page 3-25

- “Ravigneaux 4-Speed Transmission” on page 3-39
- “Lepelletier 7-Speed Transmission” on page 3-34
- “8-Speed Transmission” on page 3-43
- “9-Speed Transmission” on page 3-47

## Lepelletier 7-Speed Transmission

### In this section...

“Transmission Overview” on page 3-34

“Clutch Schedule” on page 3-34

“Power Flow” on page 3-35

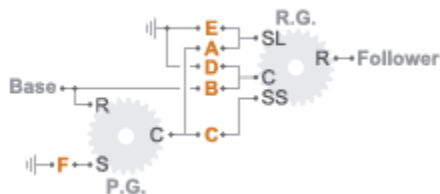
“Drive Ratio” on page 3-36

### Transmission Overview

The Lepelletier 7-speed transmission consists of one planetary gear set (P.G. in the figure), one Ravigneaux gear set (R.G.), and six disk friction clutches (A–F). The transmission base shaft connects to the ring gear of the planetary gear set. The follower shaft connects to the ring gear of the Ravigneaux gear set.

Clutches A–C control the power flow paths between the planetary and Ravigneaux gear sets. Clutches D–F serve as brakes, grounding various gears of the planetary and Ravigneaux sets to the transmission housing. In the figure, labels imposed on a gear silhouette identify the gear components:

- R — Ring gear
- C — Planet gear carrier
- S — Sun gear
- SL — Large sun gear
- SS — Small sun gear



### Clutch Schedule

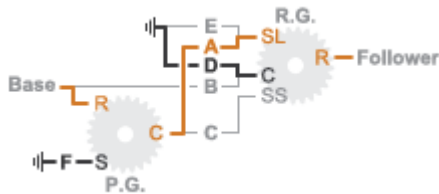
The table shows the clutch schedule of the Lepelletier 7-speed transmission. The letters in the header denote the brakes and clutches. A value of 1 denotes a locked state and a

value of 0 an unlocked state. The clutch schedule automatically generates these signals based on the Gear port input signal specified. The signals are then scaled through a Gain block and used as actuation inputs in the clutch blocks.

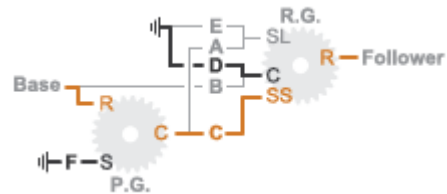
Gear	A	B	C	D	E	F
R	1	0	0	1	0	1
1	0	0	1	1	0	1
2	0	0	1	0	1	1
3	1	0	1	0	0	1
4	0	1	1	0	0	1
5	1	1	1	0	0	0
6	1	1	0	0	0	1
7	0	1	0	0	1	1

## Power Flow

The figures show the power flow paths between input and output shafts for each gear setting. Power flow is shown in orange. Connections to the transmission housing (a mechanical ground) are shown in black.



Reverse Gear



First Gear



$$g_2 = \frac{N_{RR}}{N_{RSL}},$$

$$g_3 = \frac{N_{RR}}{N_{RSS}},$$

where:

- $N_{PR}$  is the number of teeth in the planetary ring gear.
- $N_{PS}$  is the number of teeth in the planetary sun gear.
- $N_{RR}$  is the number of teeth in the Ravigneaux ring gear.
- $N_{RSL}$  is the number of teeth in the Ravigneaux large sun gear.
- $N_{RSS}$  is the number of teeth in the Ravigneaux small sun gear.

The table shows the drive ratio expressions and their default values for the various transmission gears.

<b>Gear</b>	<b>Drive Ratio</b>	<b>Default Ratio</b>
R	$-\frac{g_2(1+g_1)}{g_1}$	-3.82:1
1	$\frac{g_3(1+g_1)}{g_1}$	4.31:1
2	$\frac{(1+g_1)(g_3+g_2)}{g_1(1+g_2)}$	2.43:1
3	$\frac{1+g_1}{g_1}$	1.63:1
4	$\frac{g_3(1+g_1)}{g_3(1+g_1)-1}$	1.17:1

5	1	1:1
6	$\frac{g_3(1+g_1)}{g_2(1+g_1)+1}$	0.86:1
7	$\frac{g_2}{1+g_2}$	0.7:1

#### More About

- “CR-CR 4-Speed Transmission” on page 3-25
- “Ravigneaux 4-Speed Transmission” on page 3-39
- “Lepelletier 6-Speed Transmission” on page 3-29
- “8-Speed Transmission” on page 3-43
- “9-Speed Transmission” on page 3-47



## Ravigneaux 4-Speed Transmission

### In this section...

“Transmission Overview” on page 3-39

“Clutch Schedule” on page 3-39

“Power Flow” on page 3-40

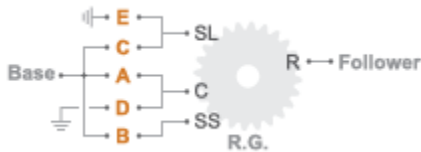
“Drive Ratio” on page 3-41

### Transmission Overview

The Ravigneaux 4-speed transmission consists of one Ravigneaux gear set (R.G. in the figure) and five clutches (A–E). The transmission follower shaft connects to the ring gear of the Ravigneaux set. Clutches A–C determine the gears that the base shaft connects to. Clutches D–E serve as brakes, grounding various gears of the Ravigneaux set to the transmission housing.

In the figure, labels imposed on a gear silhouette identify the gear components:

- R — Ring gear
- C — Planet gear carrier
- SL — Large sun gear
- SS — Small sun gear



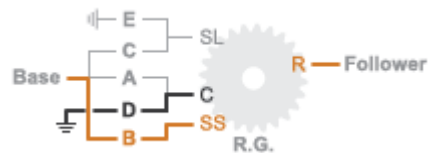
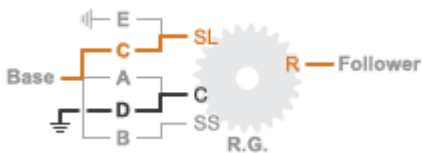
### Clutch Schedule

The table shows the clutch schedule of the Ravigneaux 4-speed transmission. The letters in the header denote the brakes and clutches. A value of 1 denotes a locked state and a value of 0 an unlocked state. The clutch schedule automatically generates these signals based on the Gear port input signal specified. The signals are then scaled through a **Gain** block and used as actuation inputs in the clutch blocks.

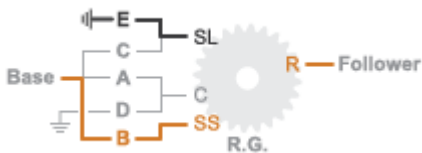
Gear	A	B	C	D	E
R	0	0	1	1	0
1	0	1	0	1	0
2	0	1	0	0	1
3	1	1	0	0	0
4	1	0	0	0	1

## Power Flow

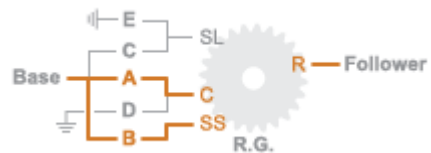
The figures show the power flow paths between the input and output shafts for each gear setting. Power flow is shown in orange. Connections to the transmission housing (a mechanical ground) are shown in black.



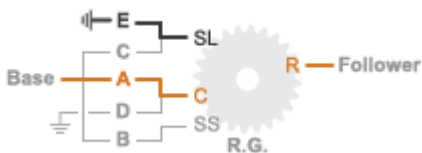
### Reverse Gear



### First Gear



### Second Gear



### Third Gear

### Fourth Gear

## Drive Ratio

The drive ratio between the transmission input and output shafts follows from the elementary gear ratios specified in the gear block dialog boxes. The elementary gear ratios are

$$g_1 = \frac{N_R}{N_{SL}},$$

and

$$g_2 = \frac{N_R}{N_{SS}},$$

where:

- $N_R$  is the number of teeth in the Ravigneaux ring gear.
- $N_{SL}$  is the number of teeth in the Ravigneaux large sun gear.
- $N_{SS}$  is the number of teeth in the Ravigneaux small sun gear.

The table shows the drive ratio expressions and their default values for the various transmission gears.

Gear	Drive Ratio	Default Ratio
R	$-g_1$	-2:1
1	$g_2$	3:1
2	$\frac{g_1 + g_2}{1 + g_1}$	1.67:1
3	1	1:1
4	$\frac{g_1}{1 + g_1}$	0.67:1

### **More About**

- “CR-CR 4-Speed Transmission” on page 3-25
- “Lepelletier 6-Speed Transmission” on page 3-29
- “Lepelletier 7-Speed Transmission” on page 3-34
- “8-Speed Transmission” on page 3-43
- “9-Speed Transmission” on page 3-47

## 8-Speed Transmission

### In this section...

“Transmission Overview” on page 3-43

“Clutch Schedule” on page 3-43

“Power Flow” on page 3-44

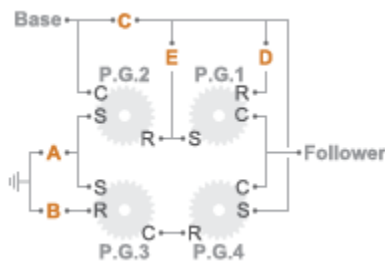
“Drive Ratio” on page 3-46

### Transmission Overview

The 8-speed transmission consists of four planetary gear sets (P.G. 1–4 in the figure) and five clutches (A–E). The transmission base shaft connects to the planet gear carrier of P.G.2 and other gears through clutches C–E. The follower shaft connects to the planet gear carriers of P.G.1 and P.G.4. Clutches A–B serve as brakes, grounding various gears of P.G.2 and P.G.3 to the transmission housing.

In the figure, labels imposed on a gear silhouette identify the gear components:

- R — Ring gear
- C — Planet gear carrier
- S — Sun gear



### Clutch Schedule

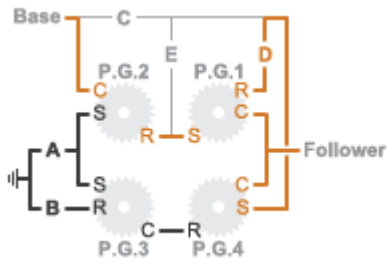
The table shows the clutch schedule of the 8-speed transmission. The letters in the header denote the transmission brakes and clutches. A value of 1 denotes a locked state

and a value of 0 an unlocked state. The clutch schedule automatically generates these signals based on the Gear port input signal specified. The signals are then scaled through a Gain block and used as actuation inputs in the brake and clutch blocks.

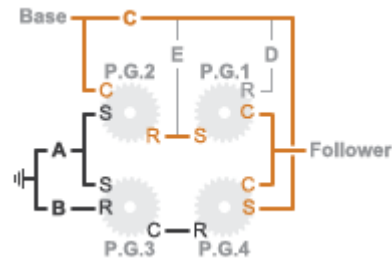
Gear	A	B	C	D	E
R	1	1	0	1	0
1	1	1	1	0	0
2	1	1	0	0	1
3	0	1	1	0	1
4	0	1	0	1	1
5	0	1	1	1	0
6	0	0	1	1	1
7	1	0	1	1	0
8	1	0	0	1	1

## Power Flow

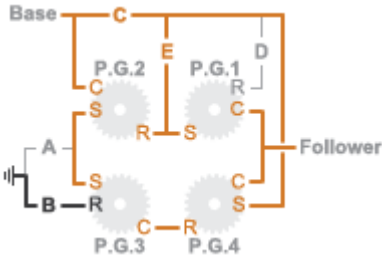
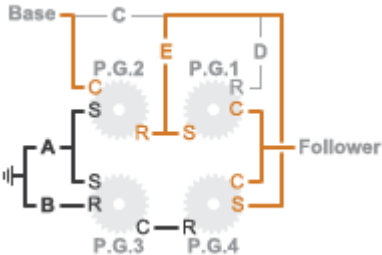
The figures show the power flow paths between the input and output shafts for each gear setting. Power flow is shown in orange. Connections to the transmission housing (a mechanical ground) are shown in black.



Reverse Gear

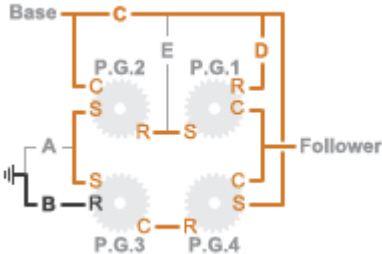
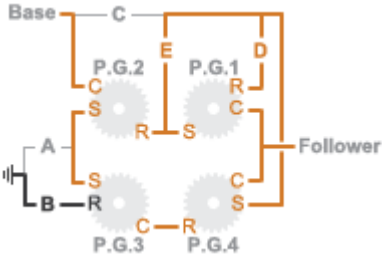


First Gear



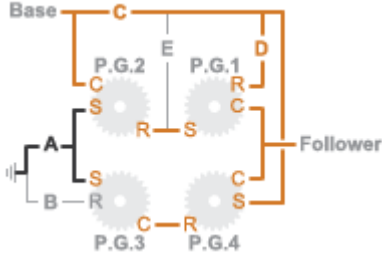
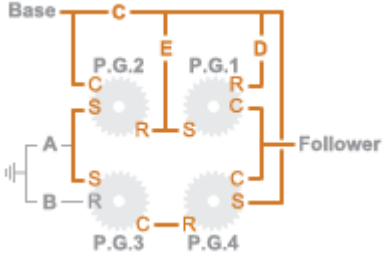
Second Gear

Third Gear



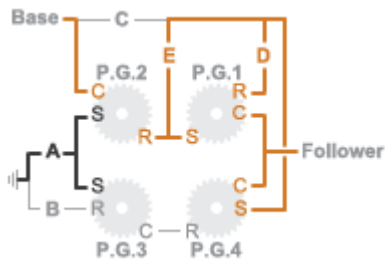
Fourth Gear

Fifth Gear



Sixth Gear

Seventh Gear



### Eighth Gear

### Drive Ratio

The table shows the default drive ratios for the various transmission gears.

<b>Gear</b>	<b>Default Ratio</b>
R	-3.91:1
1	4.55:1
2	2.96:1
3	2.07:1
4	1.69:1
5	1.27:1
6	1:1
7	0.85:1
8	0.65:1

### More About

- “CR-CR 4-Speed Transmission” on page 3-25
- “Ravigneaux 4-Speed Transmission” on page 3-39
- “Lepelletier 6-Speed Transmission” on page 3-29
- “Lepelletier 7-Speed Transmission” on page 3-34
- “9-Speed Transmission” on page 3-47



## 9-Speed Transmission

### In this section...

“Transmission Overview” on page 3-47

“Clutch Schedule” on page 3-47

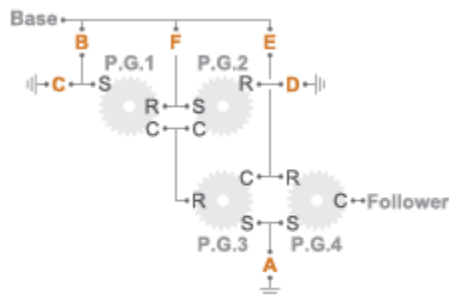
“Power Flow” on page 3-48

### Transmission Overview

The 9-speed transmission consists of four planetary gear sets (P.G.1–4 in the figure) and six clutches (A–F). The transmission follower shaft connects to the planet gear carrier of P.G.4. Clutches B and E–F determine the gears that the base shaft connects to. Clutches A and C–D serve as brakes, grounding various gears of the planetary sets to the transmission housing.

In the figure, labels imposed on a gear silhouette identify the gear components:

- R — Ring gear
- C — Planet gear carrier
- S — Sun gear



### Clutch Schedule

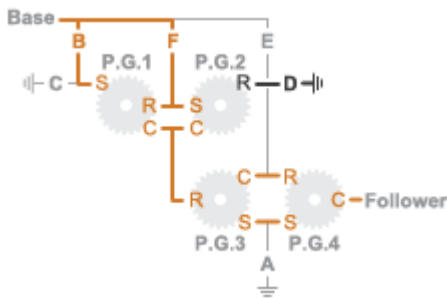
The table shows the clutch schedule of the 9-speed transmission. The letters in the header denote the transmission brakes and clutches. A value of 1 denotes a locked state

and a value of 0 an unlocked state. The clutch schedule automatically generates these signals based on the Gear port input signal specified. The signals are then scaled through a Gain block and used as actuation inputs in the brake and clutch blocks.

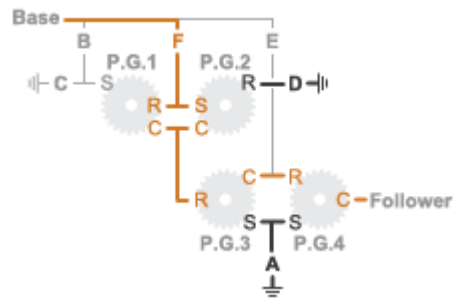
Gear	A	B	C	D	E	F
R	0	1	0	1	0	1
1	1	0	0	1	0	1
2	1	0	1	0	0	1
3	1	1	0	0	0	1
4	1	0	0	0	1	1
5	1	1	0	0	1	0
6	1	0	1	0	1	0
7	1	0	0	1	1	0
8	0	0	1	1	1	0
9	0	1	0	1	1	0

## Power Flow

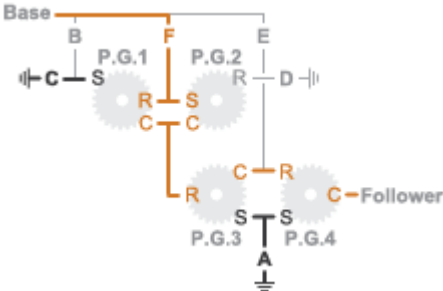
The figures show the power flow paths between the input and output shafts for each gear setting. Power flow is shown in orange. Connections to the transmission housing (a mechanical ground) are shown in black.



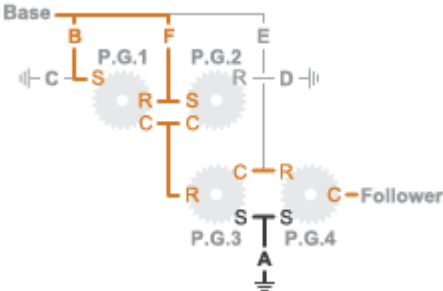
Reverse Gear



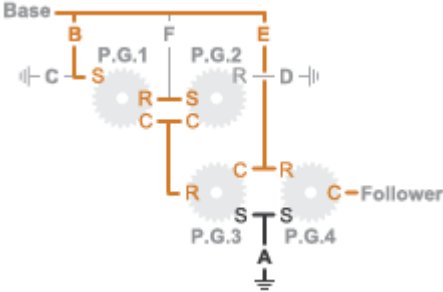
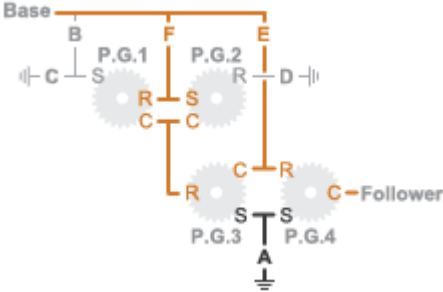
First Gear



Second Gear

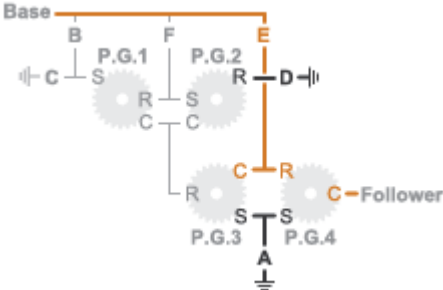
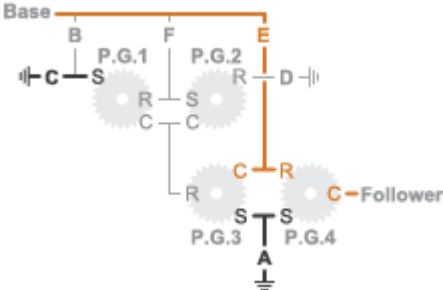


Third Gear



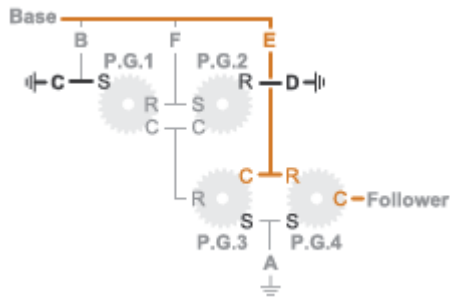
Fourth Gear

Fifth Gear

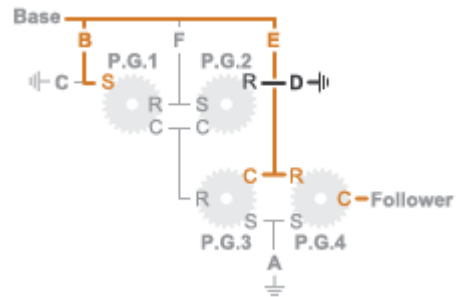


Sixth Gear

Seventh Gear



**Eighth Gear**



**Ninth Gear**

### More About

- “CR-CR 4-Speed Transmission” on page 3-25
- “Ravigneaux 4-Speed Transmission” on page 3-39
- “Lepelletier 6-Speed Transmission” on page 3-29
- “Lepelletier 7-Speed Transmission” on page 3-34
- “8-Speed Transmission” on page 3-43

# Analyzing Driveline Models and Simulations

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These sections explore some of the more complex issues in driveline modeling, as well as powerful techniques that can extend your driveline simulations.

- “Driveline Simulation Performance” on page 4-2
- “Driveline Simulation Errors” on page 4-7
- “Driveline Degrees of Freedom” on page 4-10
- “Driveline States — Effect of Clutches” on page 4-24
- “How Simscape Driveline Simulates a Driveline System” on page 4-27
- “Simscape Driveline Limitations” on page 4-28

For information about the nature of Simscape models, states, and simulation, see the Simulink documentation and the “*Simscape*” documentation.

# Driveline Simulation Performance

### In this section...

“About Simulation Performance” on page 4-2

“Adjust Model Fidelity” on page 4-2

“Optimize Simulation of Stiff Drivelines” on page 4-3

“Optimize Simulation of Clutches” on page 4-4

## About Simulation Performance

Driveline simulation involves the tradeoff between accuracy and speed inherent in all numerical simulation. Accuracy bundles two distinct issues, the accuracy or *fidelity* of the model, versus of the accuracy of the simulation methods. This section describes the inherent complexity of driveline models, as distinct from general simulation issues.

About solvers and simulation methods, see “Setting Up Solvers for Physical Models” and “Making Optimal Solver Choices for Physical Simulation”.

## Adjust Model Fidelity

Improving the fidelity of driveline models involves making blocks that are more accurate representations of the actual physical components. For example, you can make the internal dynamics of the components represented by blocks more or less accurate and realistic by:

- Turning physical effects on and off, such as nonideal gear meshing losses (gear efficiency)
- Including or omitting compliance (including damped spring reactions), hard stops, and time lags
- Including or omitting Coulomb friction from clutches and clutch-like elements
- Steepening or softening sharp gradients in physical thresholds, such as velocity thresholds in clutches and nonideal gears

Modeling these physical effects requires additional dynamics and algebraic constraints, generates computationally more intensive simulations, and can reduce simulation speed, often considerably.

### **Model Fidelity in Ordinary Desktop Simulation**

- Very small velocity threshold values and short time lags can degrade numerical convergence or simulation performance. Consider whether you can make these values larger in your simulation.
- If your model includes gears with efficiency loss, select adaptive zero-crossing in the **Model Configuration Parameters** menu.

### **Model Fidelity in Fixed-Step, Real-Time, and Hardware-in-the-Loop Simulation**

Apart from clutches, MathWorks® does not recommend including these fidelity enhancements in simulation with fixed-step solvers, particularly real-time or hardware-in-the-loop simulation.

If you do need to model compliance or efficiencies, consider reducing the number of such elements by:

- Deleting unnecessary lossy elements
- Combining lossy elements into as few elements as possible

If you simulate with a fixed-step solver, avoid:

- Very small velocity thresholds.
- Time lags that are short compared to the fixed time step.

### **Optimize Simulation of Stiff Drivelines**

When modeling a driveline, you might not need to model all compliances, depending on the purpose of your model. If there are specific compliances that are more dominant than others, then you might need to model only these compliances.

The coupling of drivelines to external loads — for an automobile, the wheel-tire-road load — is often stiff. Driving and road conditions typically change over seconds or tens of seconds. However, the internal changes of an automobile's drive system can change over fractions of a second, especially if clutch changes and braking are at work. In addition, clutch locking and unlocking events create dynamic discontinuities.

For example, a tire is “stiff” in responding slowly to imposed forces and experiencing slip. A tire also has a broad range of frequency responses. You might model tire compliance only when you model the automobile accelerating from rest.

### Optimize Simulation of Clutches

Clutch locking and unlocking events generate discontinuous changes in driveline dynamics and can cause major inaccuracies, particularly if you are simulating with a large variable-step solver tolerance or a large fixed time step.

- Clutch discontinuities change the number and nature of the degrees of freedom of the driveline during the simulation.
- Because clutch discontinuities are idealized events, they cause the driveline torques to change abruptly, as the clutch switches abruptly between static and kinetic friction.

### Smoothing and Offsetting Clutch Control Signals

You exert dynamic control on the locking and unlocking of clutches through their input pressure or other locking signals.

The simplest way to force a locking is to abruptly change a clutch pressure from zero to some predetermined value. You can then force an unlocking by abruptly changing the clutch pressure back to zero. Such abrupt clutch pressure changes are not realistic. The best solution is to model full clutch actuation. However, you can use simplified models to reduce model complexity.

You can improve your clutch modeling and make it more realistic by ensuring that the clutch pressure signals rise and fall smoothly, not suddenly. The Simulink Sources library provides many ways to create such signals. You can also reshape existing signals using blocks such as `State-Space` and `Transfer Fcn`.

These example models illustrate smoothed clutch pressure signals:

- `sdl_simple_clutch` ramps up and down the input clutch pressure.
- `sdl_vehicle` uses `Transfer Fcn` blocks to reshape and smooth sharp clutch pressure signals.

For more information about smoothing clutch signals, see “Model Realistic Clutch Pressure Signals” on page 3-16.

### Adjusting Clutch Parameters

You can adjust internal parameters within each clutch block to control when and how the clutch locks and unlocks.



### Changing Pressure or Force Threshold

The locking signal coming into a clutch is physical, with units of force or pressure. With some clutches, you can specify a force or pressure threshold  $F_{th}$  or  $P_{th}$ . This threshold imposes a cutoff on the clutch pressure such that the effective controlling pressure is  $P - P_{th}$  rather than  $P$ . If  $P < P_{th}$ , no pressure at all is applied. (Normal force between clutch surfaces can substitute for pressure.) Raising the pressure or force threshold of a clutch that has an adjustable threshold makes it harder for the clutch to engage.

---

**Tip** If a clutch in your simulation engages too easily, consider raising its pressure or force threshold. If the clutch has difficulty engaging, consider lowering this threshold.

---

### Changing Velocity Tolerance

Most clutch blocks have a velocity tolerance parameter  $\omega_{Tol}$  that controls when the clutch locks or unlocks.

- A clutch can lock only if the relative shaft velocity  $\omega$  lies in the range  $-\omega_{Tol} < \omega < +\omega_{Tol}$ .
- A clutch unlocks if the torque across the clutch exceeds the static friction limit, which depends in turn on the normal force across the clutch.

You specify  $\omega_{Tol}$  values through each clutch block.

---

**Tip** If a clutch switches between locked and unlocked too easily during simulation, consider increasing its velocity tolerance.

---

### Adjusting Solvers for Clutch Discontinuities

If you use a solver tolerance or step size that is too large, clutch discontinuities can cause major inaccuracies.

- If the variable-step tolerances are too large, the solver finds it difficult or impossible to accurately track the dynamic change associated with the change of friction torques acting on the driveline.
- If the fixed step size is too large, the solver cannot accurately resolve abrupt changes such as clutch locking and unlocking events. A fixed-step solver cannot adaptively reduce its step size to compensate.

**Tip** If you encounter convergence failures or abrupt driveline state (velocity) changes at or around the instant of clutch state changes, consider reducing the solver tolerances (for a variable-step solver) or the step size (for a fixed-step solver). Set the variable-step solver tolerance or the fixed-step solver step size to the smallest value possible that produces an acceptable simulation speed (not too slow).

---

Adjustment	Solver Type and Setting	Effect on Accuracy	Effect on Speed	Effect on Clutch Simulation
Reduce	Variable-step: tolerances	Increases	Reduces	Improves resolution and simulation of abrupt locking and unlocking
	Fixed-step: step size			
Increase	Variable-step: tolerances	Reduces	Increases	Degrades resolution and simulation of abrupt locking and unlocking
	Fixed-step: step size			

# Driveline Simulation Errors

**In this section...**

“Fix Driveline Modeling and Simulation Errors” on page 4-7

“Correct Overconstrained and Conflicting Degrees of Freedom” on page 4-7

“Correct Clutch and Transmission Errors” on page 4-8

“Correct Inconsistent Initial Conditions” on page 4-8

## Fix Driveline Modeling and Simulation Errors

A variety of errors can cause your Simscape Driveline simulation to stop before completion. Some of these errors arise from nonphysical configurations of the driveline.

## Correct Overconstrained and Conflicting Degrees of Freedom

Analyzing and counting the driveline degrees of freedom (DoFs) are essential to fixing one type of simulation error. For information about degrees of freedom, see “Driveline Degrees of Freedom” on page 4-10.

To run successfully, your driveline simulation must have a positive number of independent DoFs, from the start to the end of the simulation. Furthermore, the model DoFs must not conflict with each other.

If you encounter a simulation error where the driveline cannot move, check whether the number  $N_{\text{DoF}}$  of independent DoFs is positive, and whether the DoFs do not conflict with each other.

### Checking the Number of DoFs

If  $N_{\text{DoF}}$  is not positive:

- Remove one or more constraining blocks, such as Gears, Clutches or clutch-like elements, and Mechanical Rotational References.
- Remove one or more **Ideal Angular Velocity Source** blocks.

Try one or both of these steps repeatedly until you locate the origin or origins of the simulation failure and make  $N_{\text{DoF}}$  positive.

### Checking the Consistency of DoFs

Consider also whether two or more DoFs are in conflict. For example, check whether two velocity sources are trying to move a single DoF in two different ways. Such a configuration creates a motion conflict and leads to a simulation error.

### Correct Clutch and Transmission Errors

Faulty clutch and transmission configurations generate many driveline motion failures and usually arise from DoF conflicts and errors. Clutches impose *conditional* or *dynamic* constraints.

To avoid or solve such problems, pay close attention to the collective state of your clutches, including clutches occurring inside transmission subsystems. The key to avoiding errors with transmissions is to work out and implement a complete and consistent clutch schedule.

Common mistakes include:

- Locking too many clutches simultaneously, leading to redundant dynamic constraints and overconstrained (not enough) DoFs.
- Locking conflicts among clutches, leading to nonredundant but still conflicting constraints.

*Example:* Locking one clutch locks one driveline axis to another. You could also lock the first driveline axis simultaneously to a third axis with another clutch. If the second and third axes cannot turn at the same velocity, these DoFs are in conflict.

- Locking too few clutches simultaneously. This error does not overconstrain DoFs or put them in conflict. However, it puts a transmission into a neutral state where it cannot transmit any torque or motion.

For information about adjusting simulation for clutches, see “Optimize Simulation of Clutches” on page 4-4 and “Gears, Clutches, and Transmissions” on page 2-31.

### Correct Inconsistent Initial Conditions

Like motion sources, initial conditions can cause motion conflicts. Unlike motion sources, they do not impose constraints or remove DoFs from the driveline, because they act only at the start of the simulation. However, under certain circumstances, initial conditions can cause errors when you start the simulation:

- Initial conditions conflict with one another.

*Example:* You couple two driveline axes through a Gear with a gear ratio of 2. The base axis must spin twice as fast as the follower, in the same direction. If you actuate the base with a velocity source, and the follower is connected to an inertia with initial velocity not set to half the initial base velocity, the simulation stops with an error.

- Initial conditions conflict with motion sources. When the simulation starts, the signal controlling a velocity source acting on an axis and the initial velocity value specified on an Inertia or a Mass attached to that axis must agree. Analogous requirements hold for velocities transformed by gear couplings.

Regardless of how you set the initial conditions of your driveline axes, the complete set of initial conditions must be consistent with itself. Driveline connection lines satisfying angular velocity constraints (for example, branched lines, or lines in closed loops) must have the same initial angular velocities.

# Driveline Degrees of Freedom

### In this section...

“About Driveline Degrees of Freedom and Constraints” on page 4-10

“Identify Degrees of Freedom” on page 4-11

“Define Fundamental Degrees of Freedom” on page 4-11

“Define Connected Degrees of Freedom” on page 4-13

“Define Constrained Degrees of Freedom” on page 4-14

“Actuate, Sense, and Terminate Degrees of Freedom” on page 4-18

“Count Independent Degrees of Freedom” on page 4-19

“Count Degrees of Freedom in a Simple Driveline with a Clutch” on page 4-20

## About Driveline Degrees of Freedom and Constraints

Identifying rotational degrees of freedom (DoFs) is important for building and analyzing a driveline, particularly a complex system with many constraints and external actuations. Simulink represents driveline DoFs and other Simscape system variables as *states*, among all states of a model, including the pure Simulink states.

This section explains how to identify driveline DoFs, take constraints into account, and extract the true or *independent* DoFs from a complete driveline diagram.

- The basic elements of a driveline diagram:
  - Connection lines
  - Constraints, including branchings
  - Dynamic elements
- Sensors and sources
  - Actuating drivelines with motion sources and recording motions with motion sensors
  - Terminating DoFs

## Identify Degrees of Freedom

In a Simscape Driveline model, mechanical motions can be rotational or translational: motion around or along one axis. The simplest way to identify a driveline *degree of freedom* (DoF) is from an angular or linear velocity. A DoF represents a single, distinct angular or linear velocity. Each DoF responds to the torques and forces acting on the inertias and masses making up the driveline. Integrating Newton's equations of motion determines the angular and linear motions. Mechanical DoFs are properties of rotating inertias and translating masses. It is nonetheless consistent and simpler to identify a single Simscape Driveline DoF as a driveline axis with its connected inertias and masses.

To identify and count DoFs in a driveline, look at a Simscape Driveline diagram starting with its mechanical connection lines first, before considering its blocks. Driveline blocks modify the DoFs represented by connection lines by:

- Generating torques and forces that act relatively between driveline axes
- Adding constraints between driveline axes
- Imposing externally actuated torques, forces, and motions


For the basic rules of connection lines and ports, see “Build a Driveline Model” on page 2-3.

## Define Fundamental Degrees of Freedom

The basic unit of driveline motion is the DoF represented by an unbroken mechanical connection line. Such lines represent idealized massless and perfectly rigid driveline axes.

Represented by Inertia blocks, rotating bodies with inertias are rigidly attached to and rotate with their axes. Represented by Mass blocks, translating bodies with masses are rigidly attached to and translate along their axes. A single connection line or a set of branched connection lines represents either rotational or translational motion and must be connected to either rotational or translational ports.

### Driveline Axes as Fundamental Degrees of Freedom — Mechanical Ports

A connection line anchored by physical network connector ports  represents an idealized driveline axis. The connection line enforces the constraint that the two connected driveline components rotate or translate at the same angular or linear velocity, respectively.



You measure the angular or linear velocity of an axis with an **Ideal Rotational Motion Sensor** or **Ideal Translational Motion Sensor** block.

### Defining Relative and Absolute Angles and Positions

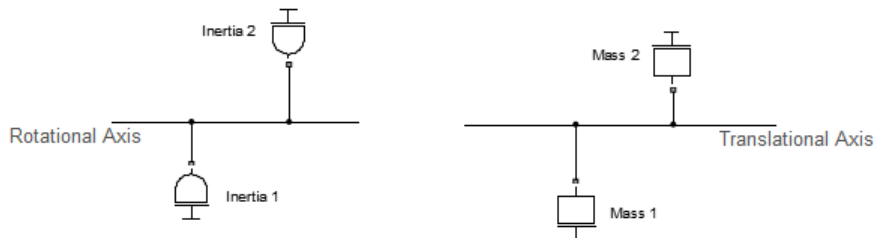
Relative angle or position is sometimes necessary to compute internally generated torques or forces between pairs of axes (see “Define Connected Degrees of Freedom” on page 4-13). To determine a relative angle or position, a motion sensor block integrates the relative angular or linear velocity of the pair of axes and adds the result to the initial relative angle or position specified in the block dialog box.

You can define an absolute rotation angle or translation position for a single axis when you measure its motion with a motion sensor, connecting the other physical connection port of the sensor to a **Mechanical Rotational Reference** or **Mechanical Translational Reference**. The sensor defines an absolute angle or position by integrating the velocity of the axis and adding the absolute reference angle or position that you provide in the motion sensor dialog box.

### Rotating Inertias and Translating Masses Attached to Driveline Axes

You cannot subject a driveline connection line, by itself, to any torques or forces, because it lacks inertia or mass. The other basic element to construct a functioning driveline model is one or more **Inertia** blocks, one or more **Mass** blocks, or both. In a real mechanical system, the spinning (or sliding) bodies carry both inertia (or mass) and DoFs.

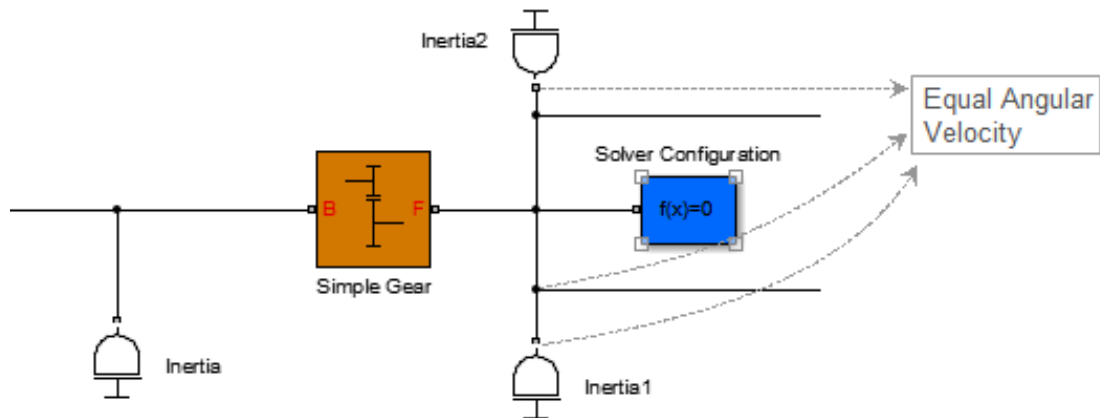
You attach Inertias and Masses to mechanical connection lines by branching the lines. The attached inertias or masses are subject to whatever torque or force is transmitted by the connection line. The connection line imposes the constraint that everything attached to a single line must be spinning or sliding at the same velocity.





## Driveline Axis Branching Rules and Constraints

You can branch connection lines. You can connect the end of any branch of a driveline connection line to a mechanical conserving connection port  $\square$  only. A set of unbroken, branched connection lines represents a single DoF.



## Branched Connection Lines and Angular Velocity Constraints

### Define Connected Degrees of Freedom

You can connect two independent driveline axes, representing two independent degrees of freedom (DoFs), by an internal *dynamic element*. A dynamic element generates a torque or force from the relative angle, position, or motion of the two axes. This torque or force acts between the two axes, which remain independent DoFs, and which transmit the torque or force to their respective attached inertias or masses.

#### Dynamic Elements — Internal Torque and Force Generation

Apart from gears, most of the Simscape Driveline library blocks are dynamic elements, as are the mechanical rotational and translational blocks of the Simscape Foundation library. These blocks generate internal torques and forces. On a block with two mechanical conserving ports, a single torque or force is applied with positive sign to one axis and negative sign to the other axis. In this figure, torque is applied equally and oppositely to the rod and case axes of the Torsional Spring-Damper.



On blocks with more than two mechanical conserving ports, the total torques or forces flowing in and out of the block still sum to zero, but the torque or force is divided among the ports in a more complex way that depends on the driveline dynamics.

### Clutch and Clutch-Like Elements — Conditional Connections

A clutch or clutch-like element is a *conditional* or *dynamic* constraint.

If unlocked, a clutch connects two driveline axes and can impose a relative torque between them, leaving the two axes independent. The unlocked clutch is either completely unengaged, imposing no torque at all; or engaged, imposing kinetic friction as a function of the relative velocity of the two connected axes.

If a clutch locks and applies only static friction between the two connected axes, the two axes are no longer independent. Instead, they act as a single axis, spinning at the same rate. See “Define Constrained Degrees of Freedom” on page 4-14.

A number of other, clutch-like blocks also have locking and unlocking Coulomb friction:

- Torsional Spring-Damper
- Loaded-Contact Rotational Friction and Loaded-Contact Translational Friction

### Define Constrained Degrees of Freedom

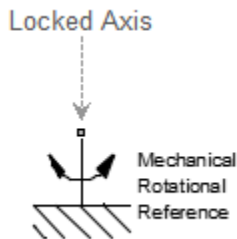
Certain driveline elements couple driveline axes in a way that eliminates their freedom to move independently. Such elements impose constraints on the motions of the connected axes. A constrained axis is no longer independent of other axes and does not count toward the total net or independent motions of the driveline. Such constraints remove independent degrees of freedom (DoFs) from the system.

Not all constraints are independent. Closing branched connection lines into loops makes some of the constraints within the loops redundant. The number of effective or independent constraints is the number of constraints arising from blocks minus the number of independent closed driveline connection line loops.

Except for clutches and clutch-like elements, driveline constraints are *unconditional* or *static* constraints; that is, unchanging over the simulation.

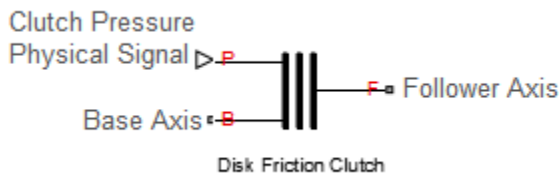
### Locking a Driveline Axis

Connecting a driveline connection line to a **Mechanical Rotational Reference** or **Mechanical Translational Reference** block freezes the motion of the corresponding driveline axis. It cannot move, and its angular or linear velocity is constrained to be zero during a simulation. Such an axis has no associated independent DoF.



### Locking Two Driveline Axes Together with a Clutch or Clutch-Like Element

As long as the conditions for locking are valid, a locked clutch or clutch-like element constrains the two connected driveline axes to spin or slide together. The two axes remain distinct, but only one represents an independent DoF. The other is dependent.

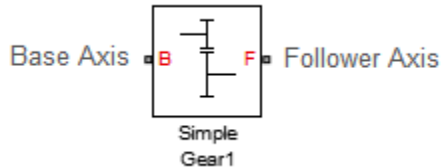


Even if it continues to apply kinetic friction between the axes, an unlocked clutch or clutch-like element no longer imposes a constraint. Instead, it acts as a dynamic element. See “Define Connected Degrees of Freedom” on page 4-13.

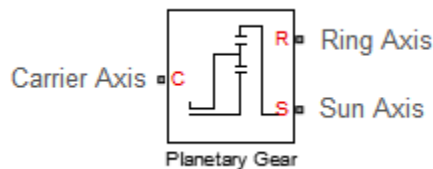
### Coupling Driveline Axes with Gears

A gear coupling between two or more driveline axes reduces the independent DoFs of the driveline by imposing constraints. The nature of those constraints depends on the gear

that you use. Gear blocks with two connected axes impose one such constraint and reduce the two axes to a single independent DoF.



Multiaxis gears impose more than one constraint. For example, a planetary gear imposes two constraints on three axes, reducing the axes to one independent DoF. (This count does not include the fourth, internal DoF, the planetary wheel, which is not connected to an axis with a mechanical port.)



### Closed Loops, Effective Constraints, and Constraint Consistency

The actual constraint count to determine the number of DoFs is the number of effective or *independent* constraints. When connection lines form closed loops, you must take extra care in counting constraints in a driveline diagram. The presence of closed loops in a diagram reduces the effective constraint count by rendering some of the constraints redundant:

$$N_{\text{constr}} = N_{\text{bconstr}} - N_{\text{loop}}$$

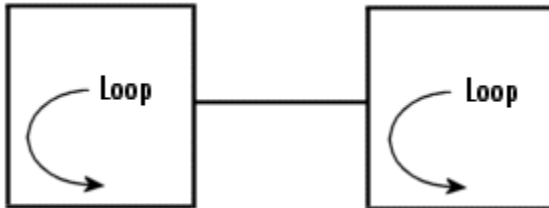
$N_{\text{constr}}$       Number of independent constraints

$N_{\text{bconstr}}$      Number of constraints from blocks

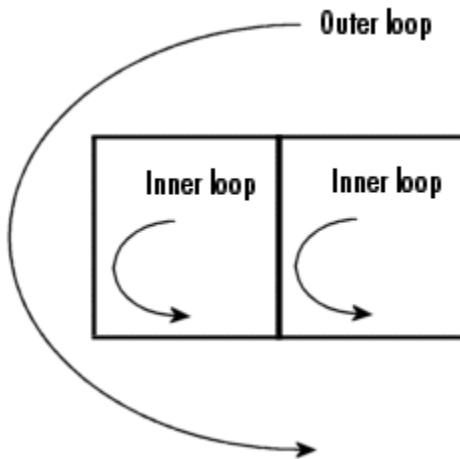
$N_{\text{loop}}$          Number of independent loops

You can reliably count the number of independent loops by counting the fundamental loops. Fundamental loops have no subloops. You can trace a fundamental loop with only one path. By counting only fundamental loops, you avoid overcounting loops that overlap.

For example, this diagram has two independent loops.



In this diagram, you can draw three loops: two inner loops, left and right, and the outer loop. The outer loop encompasses both inner loops.



There are two independent loops in this diagram, because only two are fundamental. The outer loop is not fundamental.

### **Consistency of Constraints**

As long as all the velocities constrained by line branch points are equal over the whole loop, a closed loop renders redundant one of the constraints contained within it. (See “Driveline Axis Branching Rules and Constraints” on page 4-13.) The velocities not directly connected by lines must also be consistent if, for example, they are transferred through gears.

If the velocities along a closed loop cannot be made consistent, the driveline is overconstrained and cannot move.

### **Actuate, Sense, and Terminate Degrees of Freedom**

You can use Simscape Driveline and related blocks with only one driveline connector port **□** to originate or terminate a physical connection line. Terminating a connection line limits the DoF.

Such blocks include:

- **Inertia** and **Mass**, which accept torque and force and respond with acceleration.
- **Mechanical Rotational Reference** and **Mechanical Translational Reference**, which ground DoFs to zero velocity.
- **Vehicle Body**, which implicitly connects the driveline to ground.

These blocks do not have to end a connection line, but can instead be branched off of a connection line.

### **Directionality of Degrees of Freedom**

Driveline connection lines have no inherent directionality. The direction of motion and torque flow is determined by the driveline dynamics when you simulate a model.

### **Effect of Torque and Force Actuation on Degrees of Freedom**

Connecting an **Ideal Torque Source** or **Ideal Force Source** into a driveline connection line adds the torque or force specified by a physical signal input into that driveline axis. Such an actuation has no effect on the number of system DoFs. The driveline axes transmit torques and forces to their connected Inertias and Masses. The driveline is free to respond to these imposed torques or forces. The motion is simulated by integrating the driveline accelerations (a result of the imposed torques and forces) to obtain the driveline velocities.

### **Effect of Motion Actuation on Degrees of Freedom**


Connecting an **Ideal Angular Velocity Source** or **Ideal Translational Velocity Source** to a driveline axis removes the freedom of that axis to respond to torques or forces. Instead, it specifies the axis motion during the simulation from the actuating physical signal input. Unlike torque actuation, motion actuation removes an independent DoF from the system.

For more information about driveline actuation with torques, forces, and motions, see “Driveline Actuation” on page 2-20.

## Count Independent Degrees of Freedom

To determine the number of independent degrees of freedom (DoFs) in your driveline:

- 1 Count all the continuous, unbroken driveline connection lines (grouping together connected sets of branched lines) in the Simscape Driveline portion of your model diagram. Call the total of such lines  $N_{CL}$ .

These lines connect two driveline connector ports or terminate on one mechanical connector port . For details, see “Define Fundamental Degrees of Freedom” on page 4-11 and “Actuate, Sense, and Terminate Degrees of Freedom” on page 4-18.

- 2 Count all the constraints arising from blocks that impose constraints on their connected driveline axes. Call the total of such constraints  $N_{bconstr}$ .

In most cases, each such block imposes one constraint, but complex gears impose more than one. For details, see “Define Constrained Degrees of Freedom” on page 4-14.

- 3 Count the number of independent loops  $N_{loop}$ . The effective number of constraints is  $N_{constr} = N_{bconstr} - N_{loop}$ . For details, see “Closed Loops, Effective Constraints, and Constraint Consistency” on page 4-16.

- 4 Count all the motion actuations in your driveline, by counting each motion source block. Call the total of such motion actuations  $N_{mact}$ . For details, see “Actuate, Sense, and Terminate Degrees of Freedom” on page 4-18.

The number  $N_{DoF}$  of independent DoFs in your driveline is:

$$N_{DoF} = N_{CL} - N_{constr} - N_{mact} = N_{CL} - [N_{bconstr} - N_{loop}] - N_{mact}$$

A necessary (although not sufficient) condition for driveline motion and successful driveline simulation is that  $N_{DoF}$  be positive. Count rotational and translational DoFs separately.

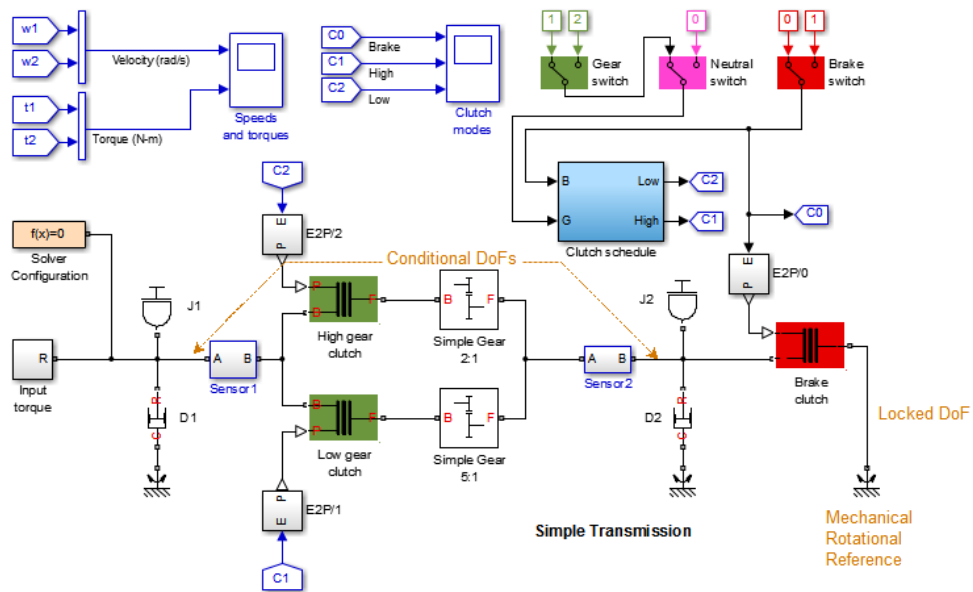
### Conditional Degrees of Freedom with Clutches and Clutch-Like Elements

Unlike other driveline components, clutches and clutch-like elements can undergo a discontinuous state change during the course of a simulation. In general, the number of independent DoFs of a driveline is not constant during its motion. Each state change of one or more clutches changes the independent DoF count. Taken as a whole, different

collective states of a driveline's clutches can have different total net DoFs. To understand a driveline completely, you must examine each possible collective state of its clutch states to identify its independent DoFs and possibly invalid configurations.

## Count Degrees of Freedom in a Simple Driveline with a Clutch

Consider the simple transmission model `sdl_simple_transmission`.



### Simple Transmission

This system has five apparent DoFs, represented by these driveline axes:

- Branched axis with J1
- Branched axis with J2



- Axis connecting the High Gear Clutch to Simple Gear 2:1
- Axis connecting the Low Gear Clutch to Simple Gear 5:1
- Axis connecting the Brake Clutch to the Mechanical Rotational Reference (rotational ground)

There is an apparent closed loop formed by the Gears and Gear Clutches. This loop is real only if both Gear Clutches are locked.

The actual number of independent DoFs depends on the state of the clutches. The model has no motion sources, so we need consider only Gears and Clutches as constraints.

- The two Gears are always acting, therefore yielding two ever-present constraints.
- The fifth axis is always connected to the Housing. These three constraints reduce five DoFs to two DoFs.

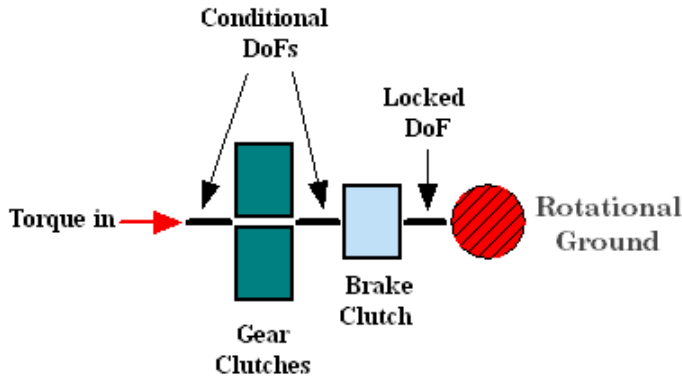
Now consider the clutches.

- Consider first the case where the Brake Clutch is disabled (free).
  - If both High Gear Clutch and Low Gear Clutch are unlocked, the system has two independent DoFs, one on the left of the Gear Clutches and the other between the Gear Clutches and the Brake Clutch.
  - If one of these Gear Clutches is locked, the additional constraint reduces the system to one independent DoF, everything to the left of the Brake Clutch. (The clutch control schedule is set up to prevent both of these clutches from being locked at the same time.)
- If the Brake Clutch is enabled, the clutch control schedule keeps the two Gear Clutches disabled.
  - If the Brake Clutch is unlocked, the driveline has two independent DoFs: to the left of the Gear Clutches and between the Gear Clutches and the Brake Clutch.
  - If the Brake Clutch is locked, the system is reduced to one DoF, to the left of the Gear Clutches. Everything to the right of the Gear Clutches is locked to the Housing.

This table and abstract diagram summarize the possibilities available in this model.

Brake Enabling	Clutch Locking	Independent DoFs
Brake disabled	Both Gear Clutches unlocked	Two: On the left and on the right of the Gear Clutches

Brake Enabling	Clutch Locking	Independent DoFs
	One Gear Clutch locked	One: On the left of the Brake Clutch
Brake enabled	Brake Clutch unlocked	Two: On the left and on the right of the Gear Clutches
	Brake Clutch locked	One: On the left of the Gear Clutches



### Degrees of Freedom in the Simple Transmission

#### Nonphysical Configurations

The clutch schedule design implemented in the Clutch Schedule subsystem excludes nonphysical configurations. It is worth considering them anyway, for the sake of a complete understanding of driveline design. For more information about clutch errors, see “Driveline Simulation Errors” on page 4-7 and “Gears, Clutches, and Transmissions” on page 2-31.

#### Both Gear Clutches Locked, Brake Clutch Unlocked

This configuration creates a conflict of DoFs and reduces the independent DoFs to one. The driveline axis to the right of the Gear Clutches tries to spin at two different rates, as required by two different gear ratios. Two locked clutches enforce two additional constraints on the two remaining DoFs, but form a closed loop, nominally leaving one freedom in the mechanism. Because of the DoF conflict, attempting to simulate such a configuration leads to a Simscape Driveline error.

If the two Gears had identical gear ratios, the DoFs would not conflict, and the simulation would run without error.

**One Gear Clutch Locked, Brake Clutch Locked**

This configuration also creates a conflict of DoFs and yields zero DoFs. The two locked clutches enforce two additional constraints on the two remaining DoFs and leave no freedom in the mechanism. Driven by the driveline axis to the left, the driveline axis between the Gear Clutches tries to spin but finds itself locked to the Mechanical Rotational Reference. Attempting to simulate such a configuration leads to a Simscape Driveline error.

**Both Gear Clutches Locked, Brake Clutch Locked**

This configuration is also overconstrained. Three locked clutches enforce two effective constraints on the remaining two DoFs (after taking into account the closed loop) and yield  $N_{\text{DoF}} = 0$ . In addition, the driveline axis to the right of the Gear Clutches tries to spin at two different nonzero rates, while at the same time remaining locked to the Mechanical Rotational Reference, creating two distinct DoF conflicts.

# Driveline States — Effect of Clutches

### In this section...

“Driveline States and Degrees of Freedom” on page 4-24

“Find and Use Driveline States” on page 4-25

## Driveline States and Degrees of Freedom

You should have some familiarity with advanced Simulink modeling techniques before using this section. For more information on driveline degrees of freedom, see “Driveline Degrees of Freedom” on page 4-10.

Simulink and Simscape represent driveline degrees of freedom (DoFs) and other information about a model's dynamics with *states*. The driveline states are a subset of the model's total states. Although the number of independent driveline states in a model is equal to the number of independent DoFs (with all clutches unlocked), the driveline states in general are linear combinations of the velocities, not the velocities of particular driveline axes. Before you simulate a model, this DoF-to-state transformation is not known.

You can extract state and model output data from your simulation. In the **Model Configuration Parameters** dialog box, select the appropriate check boxes in the **Data Import/Export** pane. The default state and output vectors are `xout` and `yout`, respectively.

### Discontinuous Clutch State Changes

In part, the overall state of the driveline is the set of all its clutch states. Because clutches are dynamic constraints, the nature of the driveline states in a model with clutches and clutch-like elements can change during the course of simulation. When a clutch locks, two independent driveline states become dependent on one another.

For software to design and analyze transitions among discontinuous states such as those found in clutches and transmissions, see Stateflow<sup>®</sup>.

### Inverse Dynamics

State information is also useful for analyzing a driveline's *inverse dynamics*. In many cases, you apply torques and forces to a driveline in *forward dynamics* and then

determine the motions. Inverse dynamics means specifying motions to determine what torques and forces to produce those motions.

If you motion-actuate some parts of your driveline instead, those axes and the equivalent states are no longer independent. If you want outputs from these axes, measure the torques and forces flowing along them. Knowing these torques and forces is the starting point of inverse dynamic analysis.

## Find and Use Driveline States

This section explains how you locate and use Simscape Driveline states.

### Locating Driveline States in Simulink

Your driveline model consists of a mixture of Simscape Driveline, Simscape, and ordinary Simulink blocks. In general, a model has Simulink states associated with the Simulink blocks. The Simscape Driveline and Simscape states of a single driveline system are associated with the Solver Configuration block of that driveline.

You can list all model states with the Simulink `Simulink.BlockDiagram.getInitialState` method:

- 1 Open a model. In this example, use `sdl_model` as an example. (This is not an example model.)
- 2 At the command line, enter:

```
sigt = Simulink.BlockDiagram.getInitialState('sdl_model');
sigt.time
sigt.signals
```

The `Simulink.BlockDiagram.getInitialState` method initializes the model at zero time and captures the model states within the `.signals` structure. This list is the total set of states, not just the independent states. The Simscape and driveline states are a subset of the total states.

### Trimming and Linearization — Clutch States

An important part of analyzing a driveline system is finding stable steady states of motion and understanding how the driveline responds to small changes in inputs, such as changes to initial conditions or to the applied forces and torques. Trimming and linearization are the formal steps of such an analysis.

If you implement clutch state changes in your simulation, trimming requires that you start by specifying which clutches are locked and unlocked. The trimming procedure then determines the state of continuous motion. During linearization, simulation starts with the clutch states that you specify and iterates to find a consistent state of all clutches. It then implements the perturbation of continuous states, holding the clutch states fixed.

For more information about trimming and linearizing Simscape models, see “Finding an Operating Point” and “Linearizing at an Operating Point”.

## How Simscape Driveline Simulates a Driveline System

### In this section...

“About Simscape Driveline and Simscape Simulation” on page 4-27

“Clutch State Determination” on page 4-27

### About Simscape Driveline and Simscape Simulation

Apart from clutches and clutch-like elements, Simscape Driveline simulation is a special case of Simscape simulation.

- For information on clutches, degrees of freedom, and states, see “Driveline Degrees of Freedom” on page 4-10 and “Driveline States — Effect of Clutches” on page 4-24.
- For information on fixing simulation errors, see “Driveline Simulation Errors” on page 4-7.
- On how Simscape models work, see:
  - “How Simscape Models Represent Physical Systems”
  - “How Simscape Simulation Works”

### Clutch State Determination

During simulation, Simscape Driveline software checks the clutch and clutch-like blocks in your model for locking and unlocking events. If a locked clutch meets the criteria for unlocking, or an unlocked clutch the criteria for locking, the respective clutch states change.

If one or more clutch and clutch-like constraints change, the driveline states are repartitioned into new sets of dependent and independent states. This requires a partial reinitialization of the driveline that preserves the driveline's state before the clutch changes, except for the subset of constraints and states affected by the clutch transitions.

# Simscape Driveline Limitations

<b>In this section...</b>
“Simscape Driveline and Simulink Limitations” on page 4-28
“Additional Simscape Driveline Limitations” on page 4-28

## Simscape Driveline and Simulink Limitations

Simscape Driveline software shares the limitations of Simscape software with respect to Simulink features and tools. For Simscape limitations, see “Limitations”.

## Additional Simscape Driveline Limitations

Simscape Driveline software also has additional limitations of its own.

### Index-2 Differential-Algebraic Equations from Variable Ratio Transmission

If you use the **Variable Ratio Transmission** block in your model, you might make your simulation slower or less accurate, depending on where the variable ratio comes from. A physical signal input defines the variable ratio as a function of time.

- If this time function is defined autonomously, independently of the dynamics of the physical system, the variable ratio is not a simulation problem.
- If this time function is defined in terms of feedback from the physical system itself, the variable ratio makes the physical-mathematical model into an *Index-2 differential-algebraic equation* (DAE) system. Its solution requires two differentiations of constraints and results in simulation warnings or errors.

To avoid this problem, do one of the following:

- Remove the Variable Ratio Transmission blocks that use physical system feedback to define their variable ratios.
- Delay the feedback signal, so that the feedback is no longer instantaneous.