

Transmission Modeling and Simulation with MapleSim[™]

Introduction

As automotive manufacturers strive to improve fuel-efficiency of their vehicles, much of the focus is on the engine as the primary source of power loss during fuel combustion. However, there is arguably as much loss through the transmission. Engineers are putting a lot of effort into assessing exactly how much power is lost, and what can be done to reduce losses and improve overall efficiency. As a result, the transmission industry is now actively involved in optimizing existing designs and exploring new innovations. These investigations are based on virtual prototypes of transmission systems, used in computer simulations. Virtual prototypes yield more efficient products at significantly reduced costs, by allowing engineers to address design issues long before they invest in the prototype. Engineering simulation products like MapleSim[™] have become critical tools in this process and are being increasingly adopted by powertrain and transmission manufacturers.

Maplesoft has developed the MapleSim Driveline Component Library, a collection of components, transmission sub-assemblies, and full-powertrain examples that show the use of the components in various driveline applications. Built with guidance from

several transmission manufacturers, the library covers all stages in the powertrain, from the engine through to the differential, wheels and road loads. It includes example transmission configurations such as manual, automatic, and dual-clutch.

One major advantage of this library is that the components use an acausal approach to model development, where the user can simply connect the components together in the required configuration without worrying about issues like torque/speed directions and load-flow. These issues are resolved automatically by the underlying solver. This makes it much easier, and significantly faster, to produce models of any complex transmission configuration from prebuilt components, compared to using traditional signal-flow simulation tools.

The library also provides “lossy” versions of many of the components that allow losses due to tooth-meshing, bearing friction, and slip to be readily incorporated, either through external calculations or through the use of empirical look-up tables. This approach allows the user to maximize the fidelity of the model while configuring the losses

to best reflect how the loss data was acquired from tests.

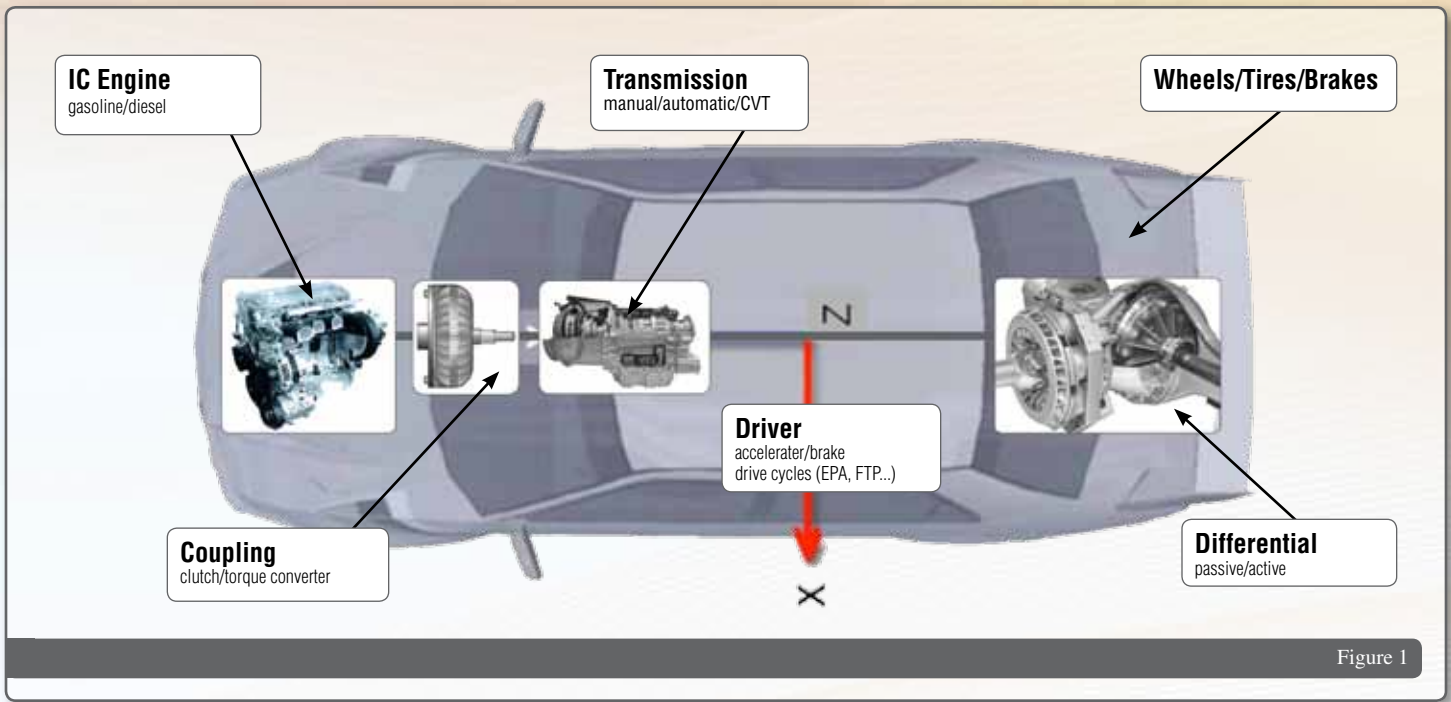
The purpose of this document is to provide some detailed description of this library, and show how the components can be used to very quickly develop complex transmission models and then test them with empirical loss data. The resulting greater insight into the overall efficiency of the system means more-informed design decisions can be made to reduce power losses and improve fuel-efficiency.

The library contains over 20 application-specific components and many examples, grouped in the following categories:

- Internal Combustion Engine
- Engine/Transmission Coupling
- Transmissions: Ideal and Lossy
- Differentials: Ideal and Lossy

The library also includes a simple driver, wheel, and road-load components that can be used as-is in your own models, or modified to suit your own needs.

The remainder of this document provides an overview of what the MapleSim Driveline Component Library provides in each of the major categories, and then examines in detail the sample models that come with the library.



Internal Combustion Engine Models

The library provides three levels of engine model, depending on the level of detail you need to include in the powertrain model:

- Controlled Torque Driver
- Mean-value
- Cycle-by-cycle

Each one can be used as-is with basic parameters to give a realistic response, but they are designed to allow you to add further detail and your own engine parameters for greater fidelity.

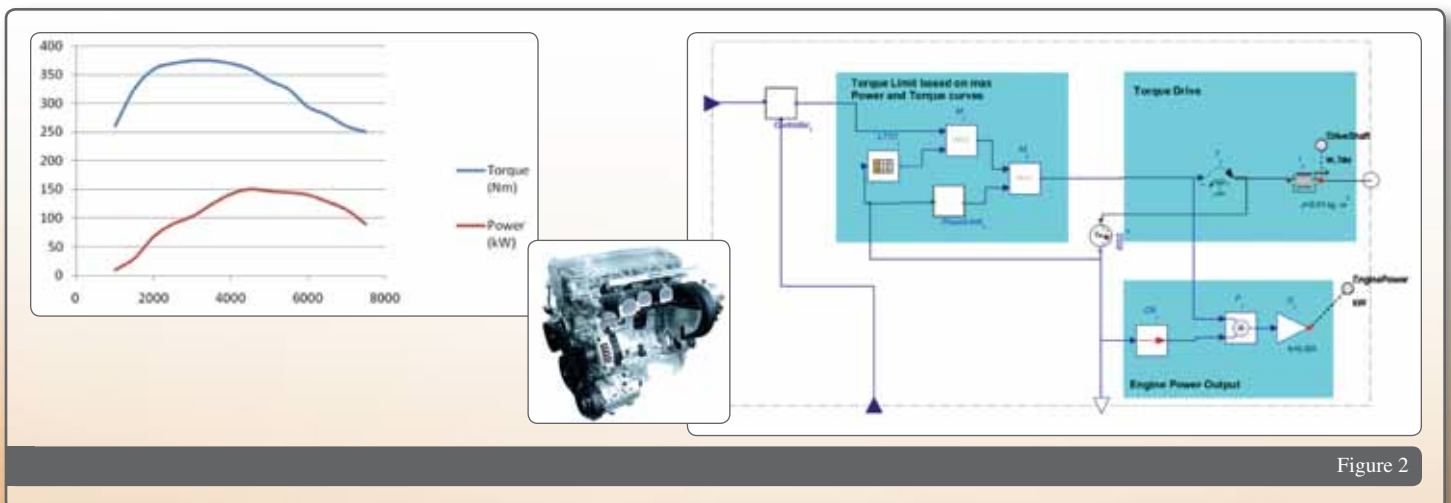
Controlled Torque Drive Engine Model

The Controlled Torque Drive is a very simple model for applications where only a torque/power output is required. It is intended to provide a first-approximation model of any type of IC engine (spark-ignition, diesel, etc.), in order to drive the rest of the driveline.

It uses a simple PID controller to output a required torque to give the desired speed.

The speed can either be the rotational speed of the driveshaft or the vehicle speed.

The engine power characteristic is determined by a lookup table of the maximum power/torque curves vs. engine speed. This is used to limit the torque output on the drive shaft.



Mean Value Engine Model

A mean-value model of an internal combustion engine provides the overall power/speed/torque output, without considering details like piston motion and ignition. Typically, these models are used for engine control development, validation, and testing.

The model incorporates acknowledged standard equations for the mass flow rate through the throttle, pressure drop across the manifold, and indicated power from combustion of the fuel, accounting for volumetric and thermal efficiencies.

More detail about this model can be found in the Maplesoft white paper, *Mean-Value Internal Combustion Engine Model with MapleSim*.

Cycle-by-Cycle Engine Model

This is a very detailed representation of the mechanical, gas-flow, and thermal elements of an internal combustion engine that considers the details throughout the 4-stroke cycle: gas intake, compression, ignition/combustion, and exhaust. It provides models of the piston/conrod/crank assembly as multibody components, with a geared connection

to the intake and exhaust valve trains, including the cams and the follower/valve/spring assemblies.

Within the combustion chamber, gas-flow, compression, combustion, and exhaust is modeled using equations from standard texts. Lost energy is assumed to be generating heat in the cylinder wall and engine block.

The model is intended to provide a comprehensive starting point and intuitive framework that can be used as-is, but also allows you to add any detail that you require for your particular application.

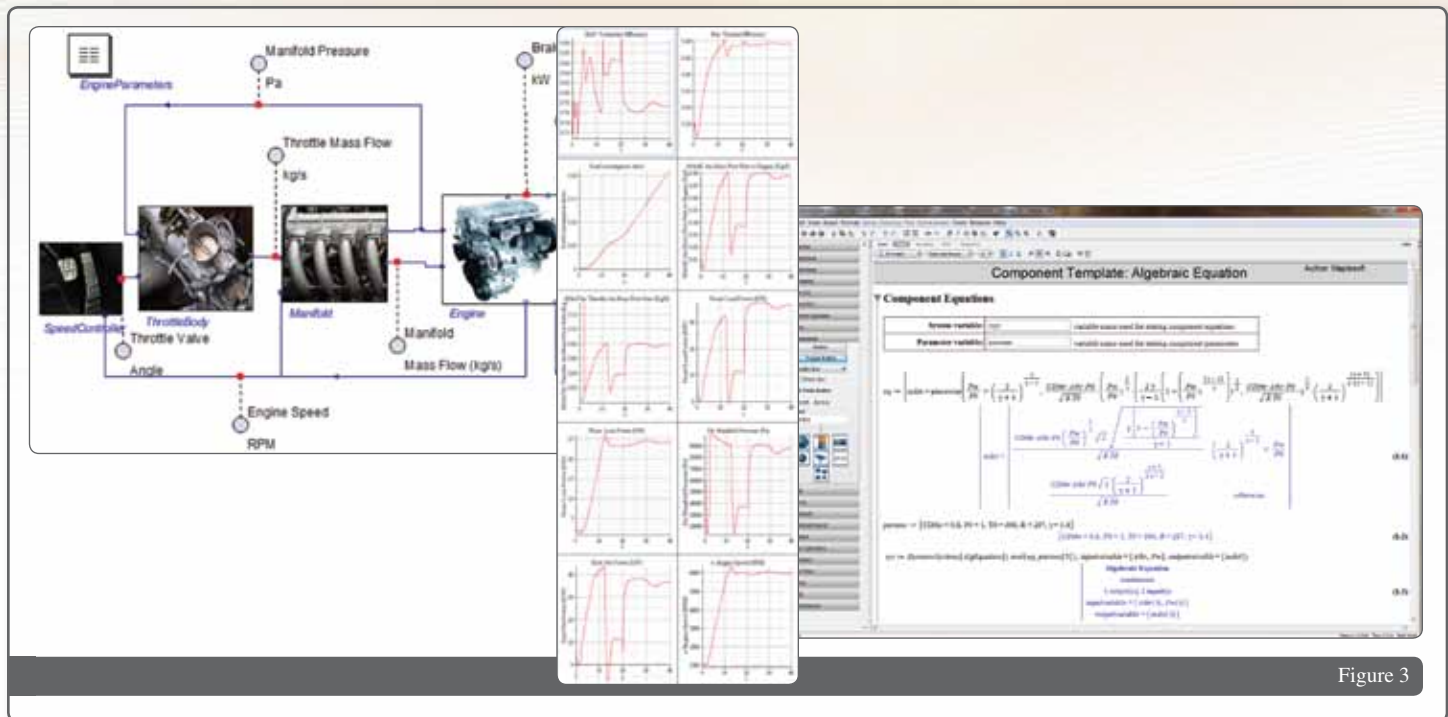


Figure 3

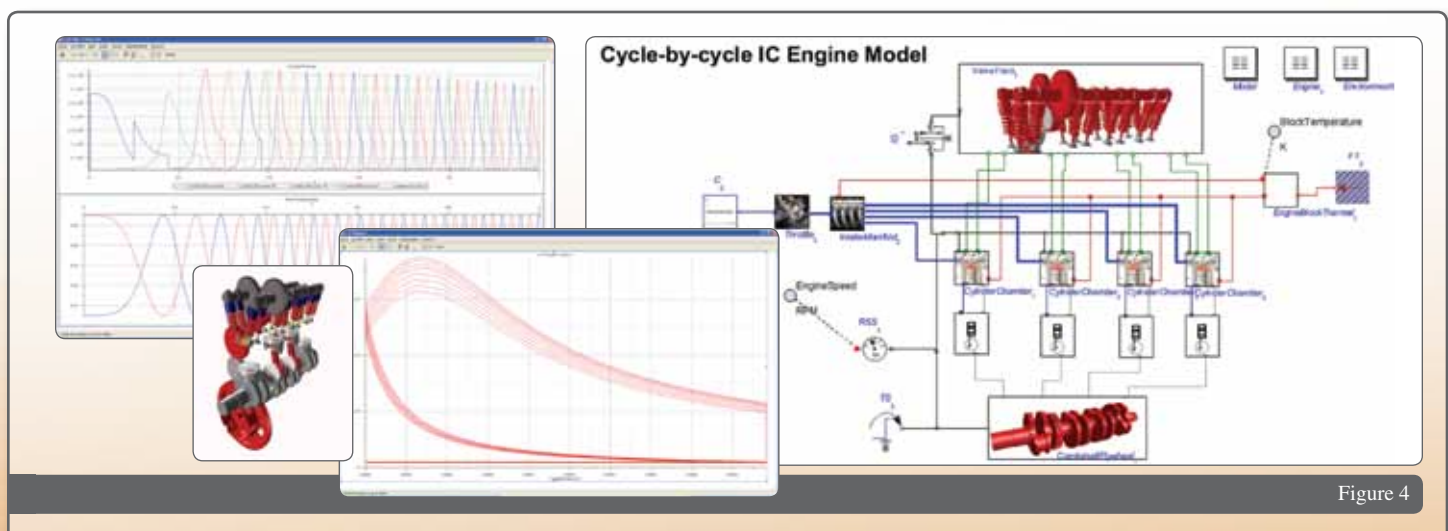


Figure 4

Engine/Transmission Coupling

In MapleSim, it is very easy to connect the drive shaft of the engine to an external mechanical system, by simply drawing a line between the “mechanical flange” ports available on each component. For example, to attach the engine shaft to an inertial load, simply connect the ports of the components to each other as shown in Figure 5.

For the purpose of modeling powertrains, MapleSim includes clutch models, and this library provides a torque converter model, which is discussed in more detail in this section.

Clutches

As part of its standard component library, MapleSim provides two clutch models: a standard, controllable friction clutch; and a one-way clutch model that provides full coupling when rotated in one direction and controlled friction coupling when rotated in the other, similar to a ratchet mechanism. Both models provide the ability to include a lookup table of friction coefficients vs. relative speed

between the friction pad and plate. Axial force on the plate(s) is provided by an input signal.

It also provides a way of entering geometric considerations, such as inner and outer pad radius and number of pad/plate assemblies.

Torque Converter

A torque converter is used primarily to provide a hydraulic coupling between the engine and an automatic transmission, although the mechanism has other applications. It is an enclosure that contains hydraulic fluid with a pump impeller on the engine side and a turbine impeller on the transmission side. During operation, the pump drives fluid into the turbine impeller, causing it to transmit torque from the engine to the transmission. It also has the property of “multiplying” the output torque to the transmission at low speeds in order to overcome friction and inertia when the vehicle is at a standstill.

Typically, the torque converter is modeled by implementing a lookup table of torque ratio (τ_o/τ_i) and load capacity vs. speed ratio (ω_o/ω_i). These characteristics will differ depending on the torque-flow, which is either driven by the engine ($\omega_o/\omega_i < 1$) or by the transmission when the vehicle is coasting ($\omega_o/\omega_i > 1$).

In the test model shown in Figure 8, the input (pump) torque increases and the transmission (turbine) torque closely matches it with a slight lag. However, due to inherent inefficiencies in the mechanism, the turbine speed is slightly less than the pump speed while the torque is driving the pump. Note that when the input torque drops at $t = 15$ s, the inertia in the transmission load changes the torque flow and the turbine drives the pump, and the pump speed drops below the turbine speed.

Note also that at low speeds, between $t = 0$ and 4 s, the turbine torque increases faster than the input torque. This is the “torque multiplication” effect, mentioned above.

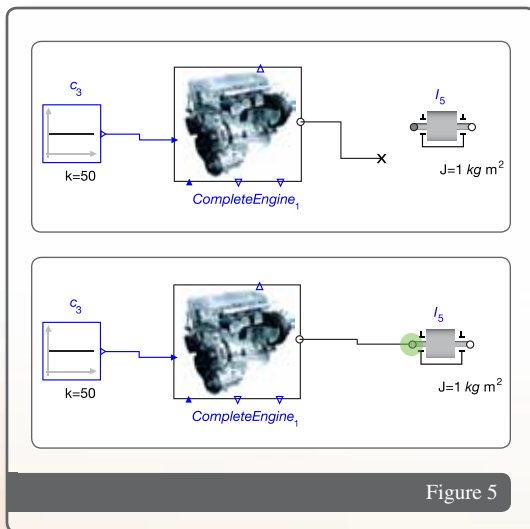


Figure 5

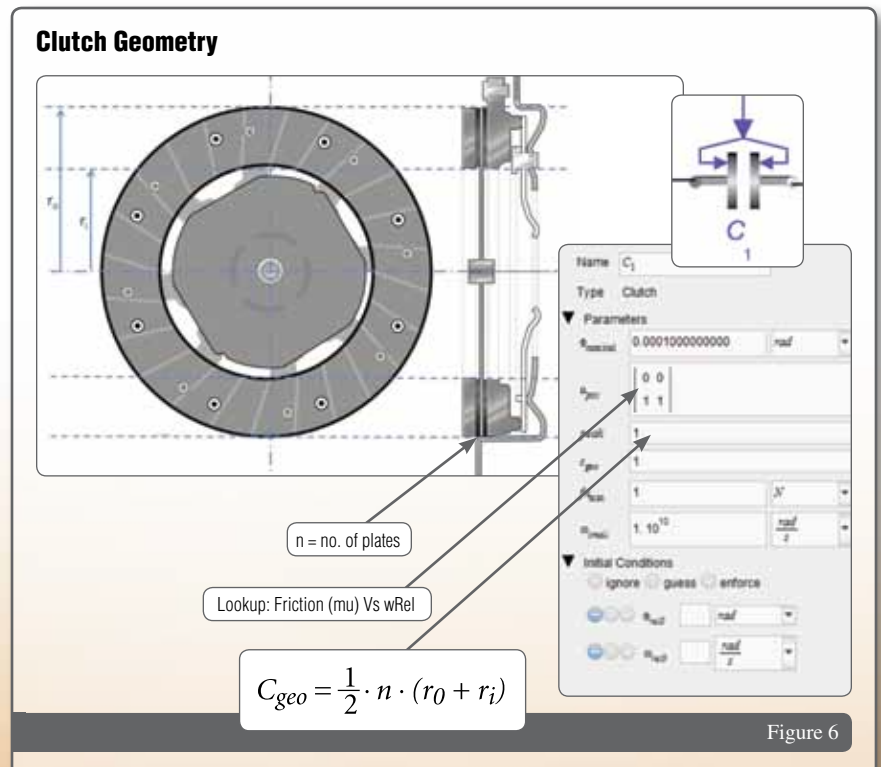


Figure 6

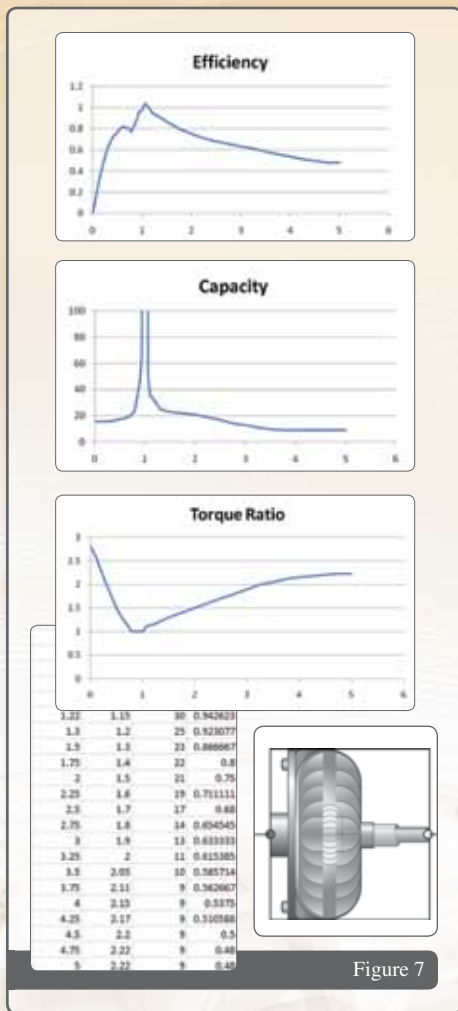


Figure 7

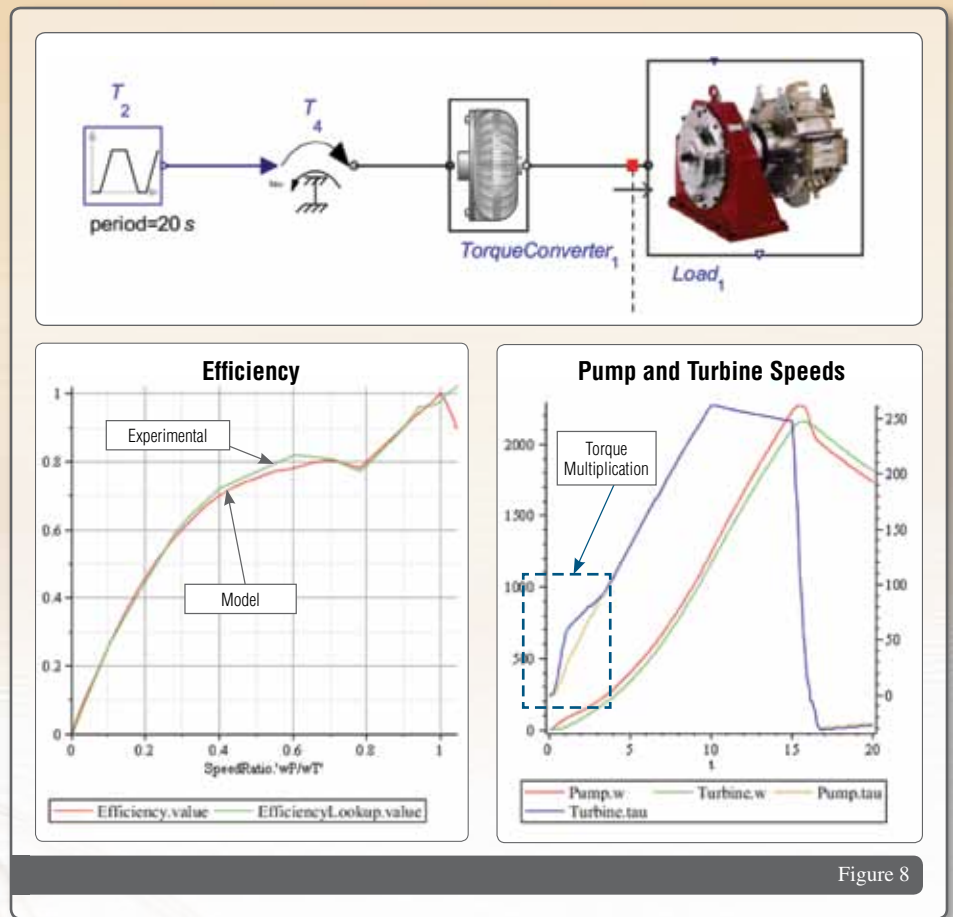


Figure 8

Transmissions

The transmissions section of the library has two subsections: basic gearing components; and example gearing configurations that use these basic components.

MapleSim includes several gearing components in its standard library, including ideal and lossy in-line gears, and the planetary gear.

Planetary Gear

The planetary gear is one of the basic configurations for many automatic transmissions. It is made of three gears: the sun gear at the center of rotation; the planet that is mounted on a carrier arm that rotates around the sun and meshes with the sun; and a ring that meshes with the planet and rotates around the same axis as the sun. The advantage of this configuration is that it provides up to six different gear ratios, depending on which gear shaft is the input, which is the output and which is clamped, as shown in the table in Figure 9 .

The base gear ratio is given by $nRing/nSun$ where $nRing$ = the number of teeth in the ring and $nSun$ = number of teeth in the sun. The number of teeth in the planet is constrained to be $\frac{1}{2}*(nRing - nSun)$.

The basic planetary gear model is part of the standard 1-D rotational mechanical component library in MapleSim.

“Decomposed” Planetary Gear

This library adds two fundamental gear components that are essential building-blocks for transmission models: the Planet-Planet and the Planet-Ring. With these two components you can create many other planetary configurations. Some of these are presented as example configurations in this document.

The first example is the planetary gear itself, which forms a basic transmission. This can be “decomposed” into a Planet-Planet gear pair, where the inner planet is the sun wheel, rotating coaxially with the drive shaft, and a Planet-Ring gear pair,

where the carrier ports are connected together and exposed as the planetary carrier port, and the outer planet in the Planet-Planet is directly connected to the planet in the Planet-Ring . The component has two parameters: the number of teeth on the sun ($nSun$) and the number of teeth on the Ring ($nRing$).

In this configuration, the outer planet in the Planet-Planet component (*planet1*) is connected to the planet in the Planet-Ring component (*planet2*). The number of teeth on the planet ($nPlanet$) is calculated using $nPlanet = (nRing-nSun)/2$ and this is the same for *planet1* and *planet2*, effectively making them the same gear.

Parameters required:

- $nSun$: # teeth on the sun gear
- $nRing$: # teeth on the ring

Note: If the number of teeth is unknown, you can simply implement a ratio by entering 1 for $nSun$ and the ratio for $nRing$.

Gear ratio depends on which gear is clamped...

Input	Output	Clamped	Ratio	[$nRing = 100, nSun=50$]
Sun	Ring	Planet	$-\frac{nRing}{nSun}$	-2
Sun	Planet	Ring	$\frac{nRing}{nSun} + 1$	3
Planet	Ring	Sun	$\frac{nRing}{nRing + nSun}$	$\frac{2}{3}$
Planet	Sun	Ring	$\frac{nSun}{nRing + nSun}$	$\frac{1}{3}$
Ring	Planet	Sun	$\frac{nRing + nSun}{nRing}$	$\frac{3}{2}$
Ring	Sun	Planet	$-\frac{nSun}{nRing}$	$-\frac{1}{2}$

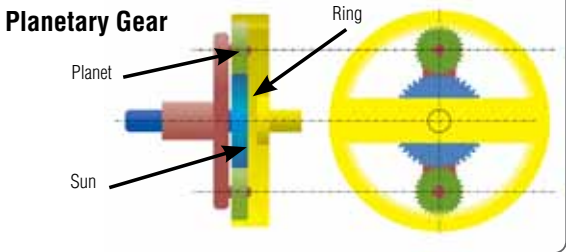


Figure 9

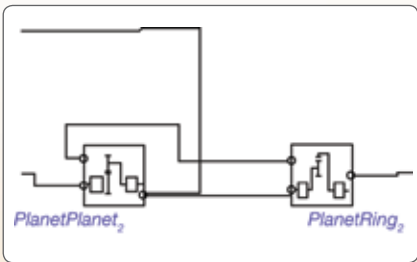
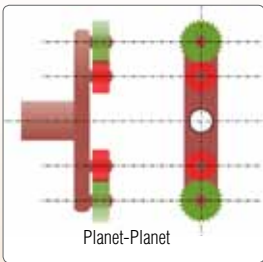
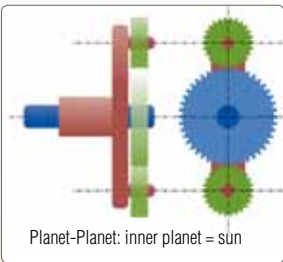
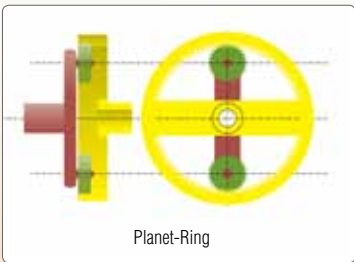
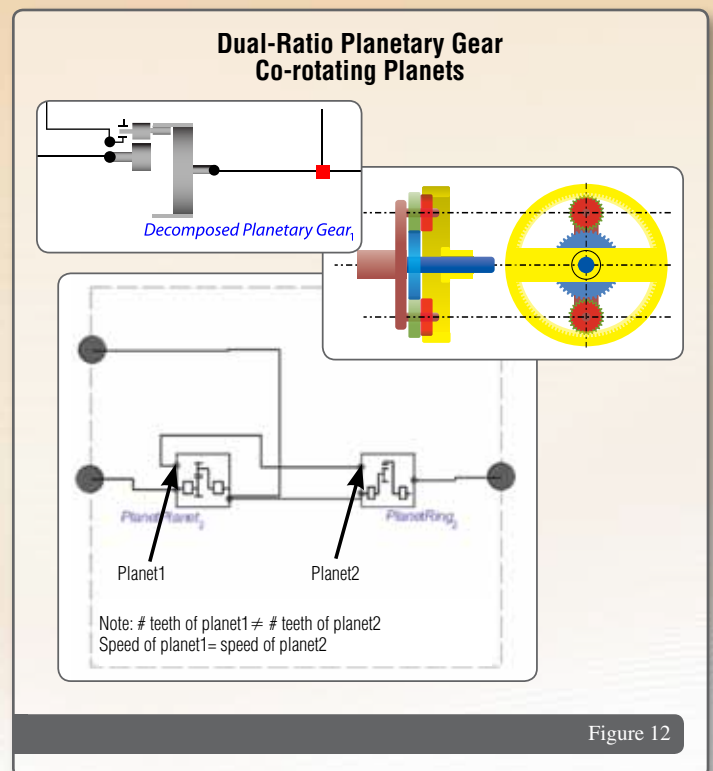
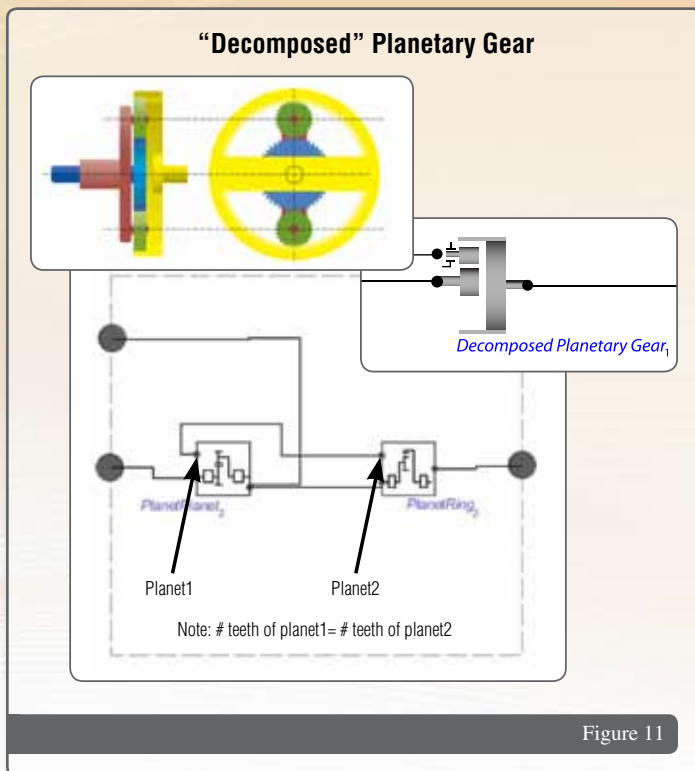


Figure 10



Dual-Ratio Planetary Gear: Co-rotating Planets

There are two configurations for a dual-ratio gear: co-rotating, where the second planet is on the same shaft as the first but the number of teeth is different; and counter-rotating, where the planets are on separate shafts but connected on the same carrier.

The co-rotating gear uses the same configuration as the planetary gear, but the number of teeth for both planets must be provided.

Parameters required:

- n_{Sun} : # teeth on the sun gear
- n_{Ring} : # teeth on the ring
- $n_{Planet1}$: # teeth on inner planet
- $n_{Planet2}$: # teeth on outer gear

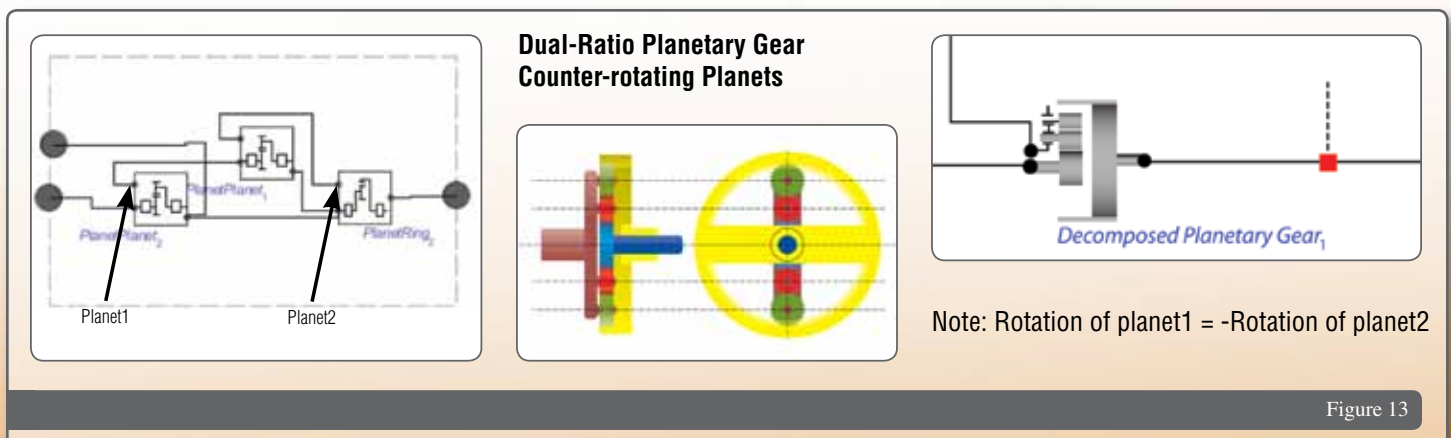
Dual-Ratio Planetary Gear: Counter-rotating Planets

This configuration adds a Planet-Planet component to the basic planetary gear to represent two planets rotating around the sun and connected on the same carrier. The

overall effect is to reverse the rotation of the ring, relative to the sun.

Parameters required:

- n_{Sun} : # teeth on the sun gear
- n_{Ring} : # teeth on the ring
- $n_{Planet1}$: # teeth on inner planet
- $n_{Planet2}$: # teeth on outer gear



Ravigneaux Gear Set

The Ravigneaux configuration is a basic automatic transmission planetary assembly. It uses a large sun gear and a small sun gear, with two independent planetary gears connected to a rotating carrier. The inner and outer planets rotate independently of the carrier, but counter-rotate with a fixed gear ratio. The inner planet meshes with the small sun gear and the outer planet meshes with the large sun gear. The ring gear then meshes with the outer planet and couples the gear-train together.

The configuration is constructed using three Planet-Planet components and one Planet-Ring component, connected as shown in Figure 13, providing mechanical ports for:

- Small sun
- Large sun
- Carrier
- Ring

The following parameters are required:

- # teeth on large sun
- # teeth on small sun
- # teeth on ring

Selection of the required gear ratios is achieved by coupling or decoupling the mechanical ports with other shafts or with the gear housing, by means of clutch components as shown in Figure 14. The clutch states for each gear, and resulting gear ratio, is given in the table shown in Figure 15.

The clutch states can be implemented as a lookup table, as illustrated in some of the powertrain models provided with the library.

Continuously Variable Transmission (CVT)

A continuously variable transmission (CVT) allows changes in gear ratio without the “bumps” experienced with

discrete gear changes. Mechanically, a CVT has two conical pulleys, connected by a belt drive. Changes in ratio are effected by adjusting the gap between the two sides of the pulleys, thus changing the relative diameters of the pulleys, and hence the gear ratio. This mechanism is not new, but has not enjoyed popularity in automotive applications because the slip between the belt and pulleys makes them very inefficient. However, advances in technology, including the use of chain drives, have made CVTs more viable, and an increasing number of vehicles that use them are now in production.

The CVT can be modeled as a standard gear set with ratio input as a signal. In response to the observation that slip can differ depending on the direction of rotation, the slip factor, $1 - \omega_o/\omega_i$, can be entered as two different signals, one for forward and the other for reverse rotation.

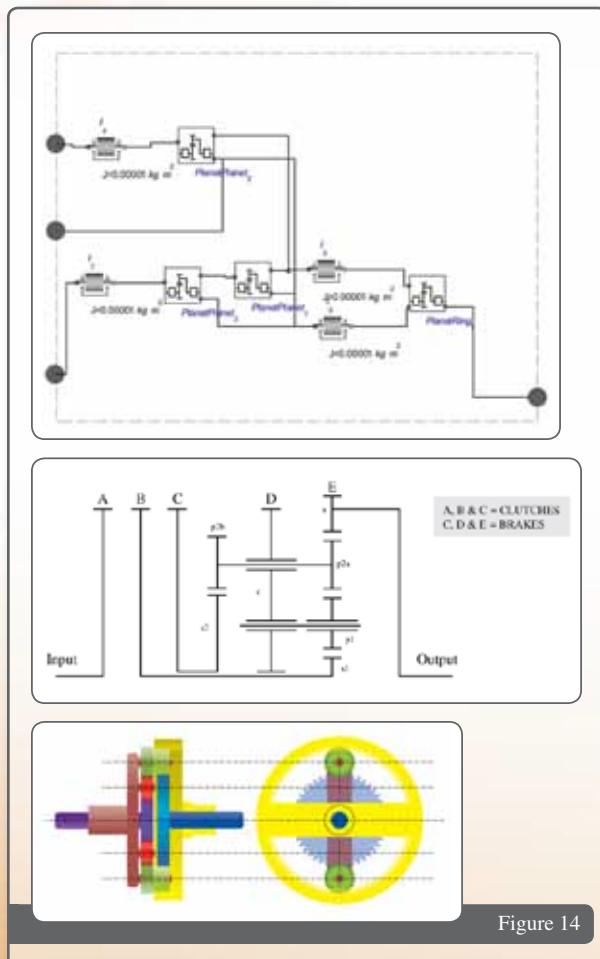


Figure 14

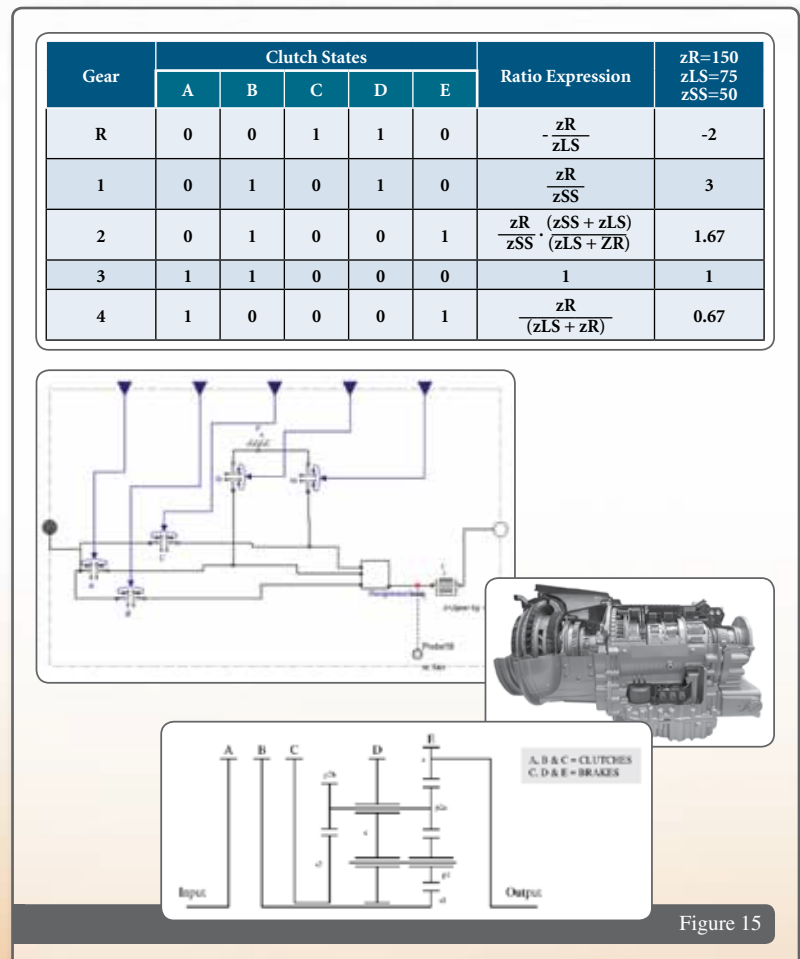


Figure 15

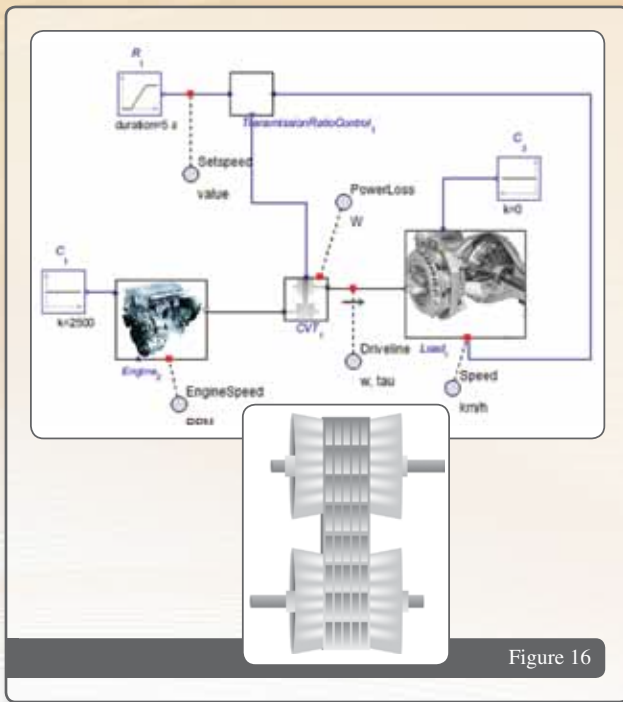


Figure 16

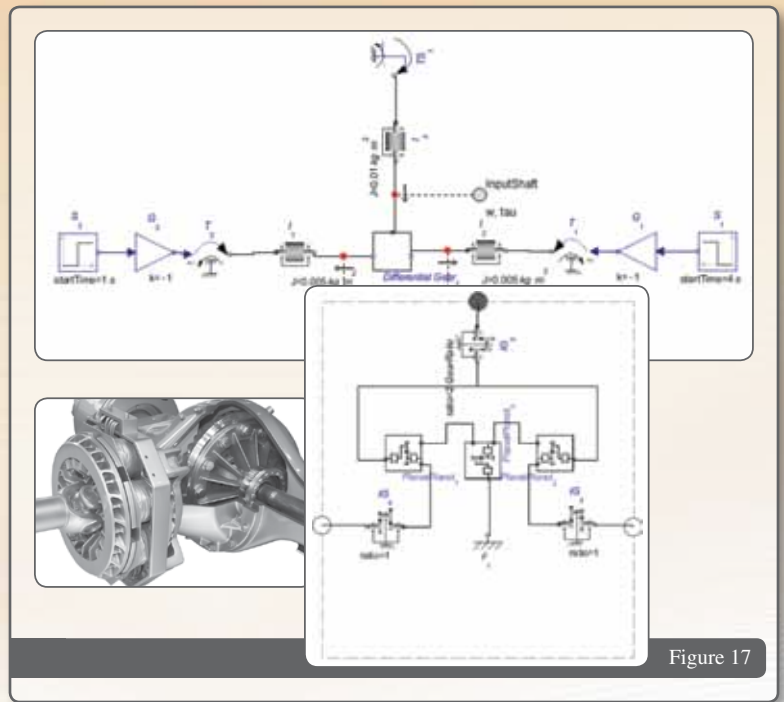


Figure 17

Differential

The differential provides a means of splitting power provided by an input shaft over two output shafts. Typically, this is used to balance the power to the left and right wheels on the drive axle, particularly when the vehicle is turning so the inner wheel needs to turn slower than the outer wheel. They are also used for other applications, such as power splitting between front and rear in four-wheel drive vehicles.

The mechanical configuration can be seen in Figure 17, where the input shaft from the transmission is connected to a bevelled crown wheel, which in turn rotates two gears on a carrier, which then

mesh with gears that are connected to each of the two output shafts.

The differential model uses three Planet-Planet components for the crown/carrier/planet assembly, meshing with simple gears that drive the output shafts. The input parameter is the overall gear ratio.

Active Differential

While they address the issue of providing different wheel speeds during turning, differentials suffer from a major weakness: they will always provide greater torque to the least loaded wheel. This can be a cause of inefficiency at best, and instability at worst. For example, in a turn, the inner wheel has less load. If too much power is applied, more torque

is applied there, and can cause the wheel to slip. Various techniques have been developed over the years to limit the torque to the least-loaded wheel, such as limited slip differentials, but these work by taking power out of the drive shaft and not by diverting it to the opposite wheel.

The active differential provides a mechanism for diverting the torque to the least loaded wheel, thus providing greater stability while improving efficiency. This model does this through the use of a CVT mechanism that changes the torque distribution in response to a signal from a controller. In this way, it is possible to electronically link the steering with the differential to optimize the power distribution to each wheel.

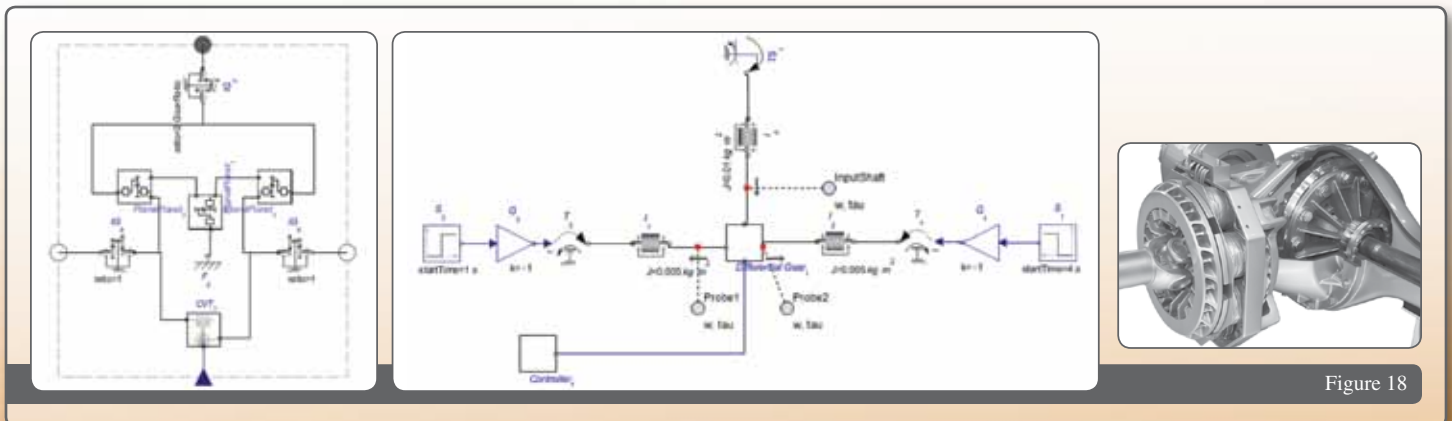


Figure 18

Incorporating Loss Data

This library provides all the mechanical building blocks you need to build any driveline system model to the level of detail required for your application. These components are based on ideal energy-conservation laws, and do not account for any energy losses within the gear. To address this, the library also includes “lossy” versions of all the basic components, which allow you to incorporate loss information as input signals to increase the fidelity of your models. These signals can either be the results of calculations performed elsewhere in the model, or interpolated loss factors from lookup tables of measured data.

For gears, the loss inputs account for meshing and bearing friction (lost energy through friction between the gear teeth and the shaft bearings, respectively) needs to be treated separately. This is because meshing friction is expressed as a transmission efficiency ($\eta_{MF} = \tau_{out} / \tau_{in}$)

and is related to the net torque between the gears as well shaft speed, while the bearing friction is expressed as a torque loss and is related only to the shaft speed. This approach also accommodates differences in losses that may depend on the direction of rotation.

The CVT component accounts for these losses, as well as slip, which is a function of transmitted power: torque * speed. The meshing friction factor can be used for chain-drive configurations, if needed.

This approach means that you have full control over how the loss data is implemented, so that it best matches how you acquired the data from tests.

For example, in the case of the planetary gear set, using the decomposed model allows you to implement loss data between the sun-planet pair and the planet-ring pair. Depending on how the data was measured, the appropriate shaft can be selected for the speed used in the

lookup table. The lossy gear component expects four loss factor inputs: meshing friction efficiency in the positive and negative torque directions, and bearing torque loss in the positive and negative rotation directions.

The simulation results for this example show the loss of speed at the input and output shafts, given a certain applied torque.

This approach is applied to all the transmission components and these are provided in this library as a parallel collection for the following:

- Simple gear
- Planetary gear
- Planet-planet & planet-ring
- Dual ratio planetary (co- & counter-rotating planets)
- Ravigneaux gear
- CVT
- Differential (passive and active)

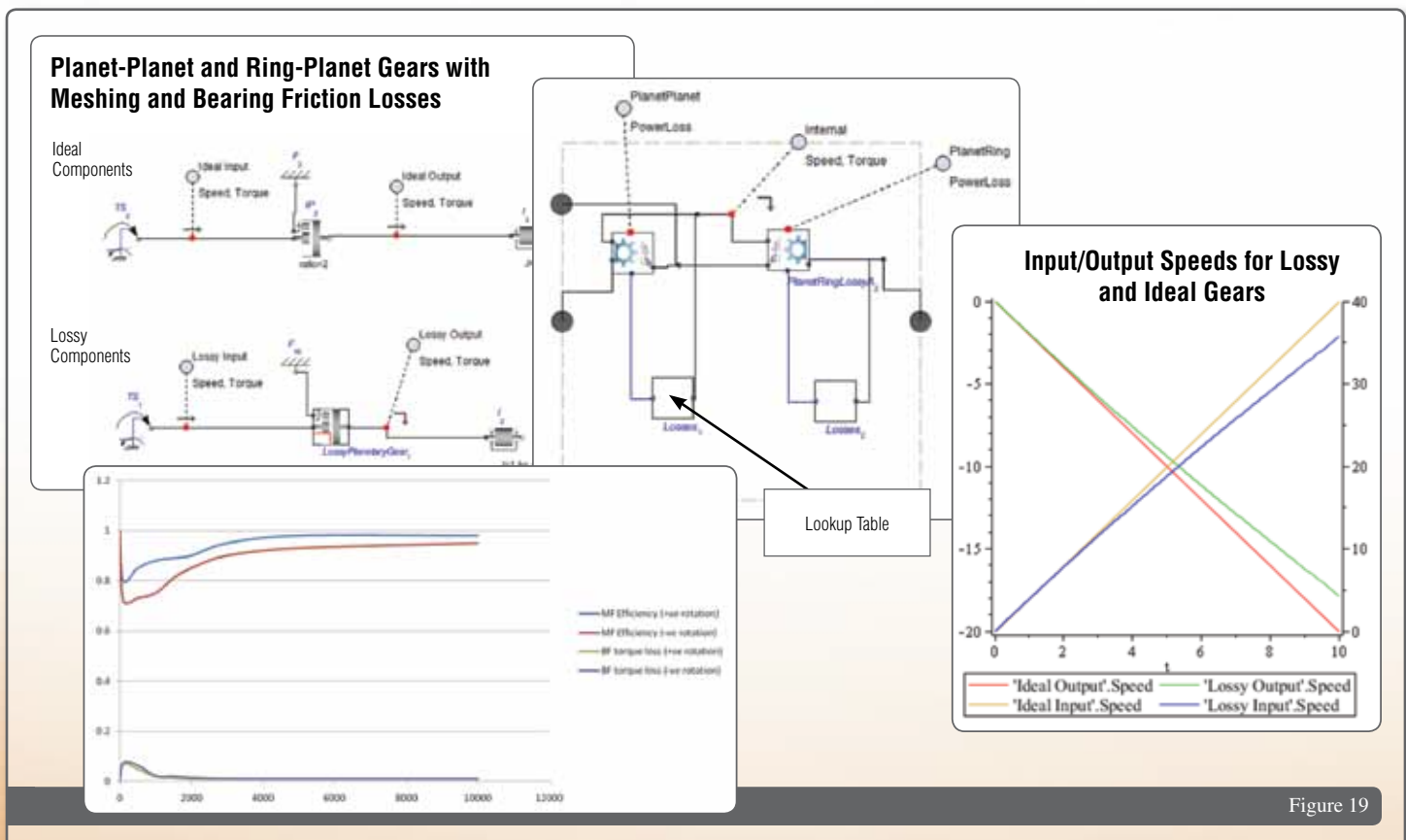


Figure 19

Example Powertrain Models

This library provides several example models to illustrate how the driveline components can be used to build full powertrain system models. At present, we provide:

- 5-speed manual transmission
- ZF 4HP22 automatic transmission
- 4-speed Ravigneaux
- 6-speed dual clutch transmission

5-speed Manual Transmission

This example uses the mean-value engine model to drive a manual transmission, coupled by a manual clutch. The powertrain is connected to a dynamometer model that not

only applies a dynamic load, but also performs a rotation-to-translation conversion to factor in the vehicle mass/inertia and compute the road speed. The vehicle speed is fed into a simple driver model – essentially a PID controller – to compute the required throttle angle for the engine model.

Since the engine model simulates the gas flow through the throttle, and the air/flow ratio is known, it is possible to calculate the fuel consumption throughout the drive cycle.

The manual transmission is made with individually selected gears at the required

ratios. The gear selector is modeled with a clutch component that engages a single gear, depending on the gear number supplied by an external signal (in this case, coming from the drive cycle lookup table), and disengaging the others. The GearSelector subsystem is a simple logic system that takes in the gear number and sets the required clutch signal to “high” and the others to “low”.

This particular example implements a 5-speed box, but it is very easy to add more gears by adding more SelectedGear subsystems and the necessary logic in the GearSelector subsystem.

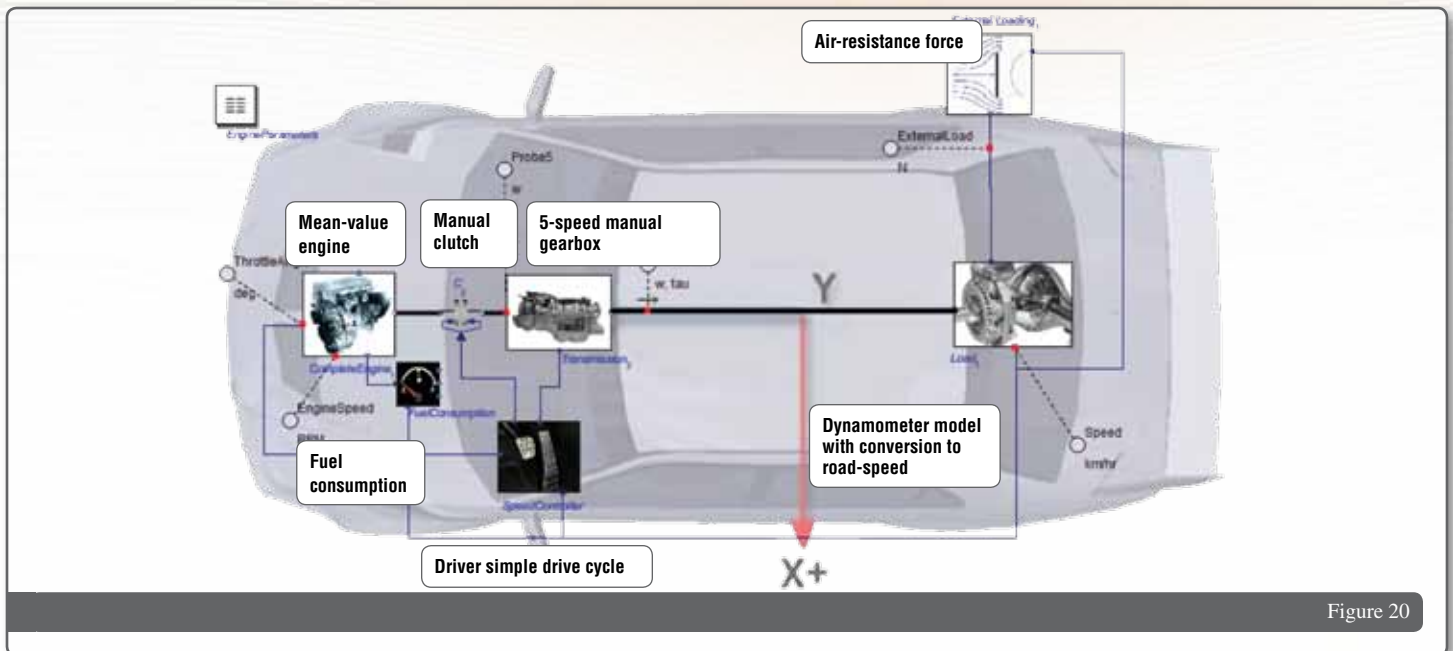


Figure 20

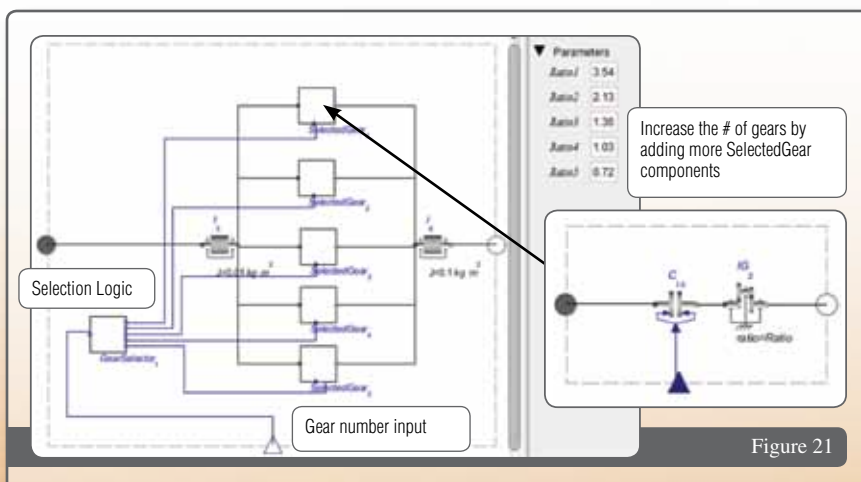


Figure 21

The loading model is in two parts: internal and external. The internal loading system is in the “Load” subsystem, and provides inertial and friction loads, as described earlier. The external loading can be provided as a signal into the Load subsystem. In this example, the air drag is calculated as a function of vehicle speed. Any loading, such as gravitation (uphill, downhill) effects, can be added in this way.

The drive cycle is provided by an input file that provides the desired speed, selected gear, and the state of the clutch during gear selection over time. Essentially, this simulates what a driver would do to change gear in a manual transmission vehicle. In this example, the vehicle is accelerating up to 120 km/h, moving through the gears at predetermined times.

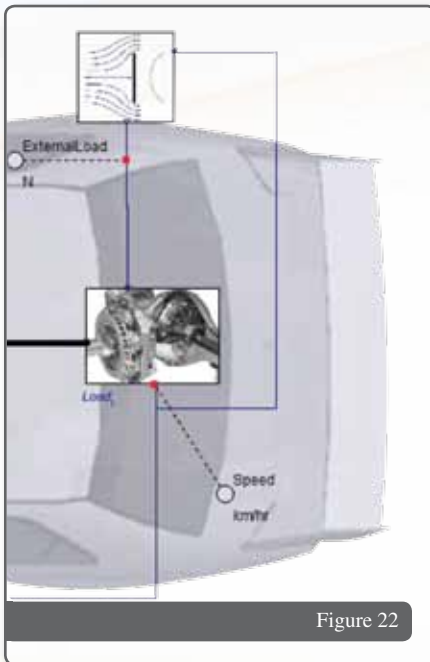


Figure 22

The results show the behavior of the engine and vehicle during the drive test. The engine revs up until the gear is changed and the revs drop. The revs then increase to about the same maximum as before. The vehicle speed matches the desired speed very closely. We can see that the fuel consumption starts quite high at the initial startup, and then falls to settle at a steady consumption value of about 5 litres/100 km, which is in the expected range, but probably very optimistic.

ZF 4HP22 4-speed Automatic Transmission

This example models a specific automatic transmission from German manufacturer, ZF, coupled to the simple controlled torque engine model via a torque converter. This transmission

model is based on a published gear schematic of the ZF 4HP22 that uses three connected planetary gears to provide four gear ratios. Gear ratios are selected by engaging and disengaging clutches in a specific pattern, shown in the clutch selection table below, and provided with the model as a lookup file.

The desired vehicle speeds and selected gear over time are provided by a drive-cycle input file. This is a simple run through the gears as the vehicle accelerates from 0 to 120 km/h.

The results from the simulation show the behavior of the engine and vehicle are as expected. The engine revs to a maximum speed, and then drops as the gear is changed. On the bottom plot we see that the vehicle speed closely tracks the speed set point from the drive cycle file.

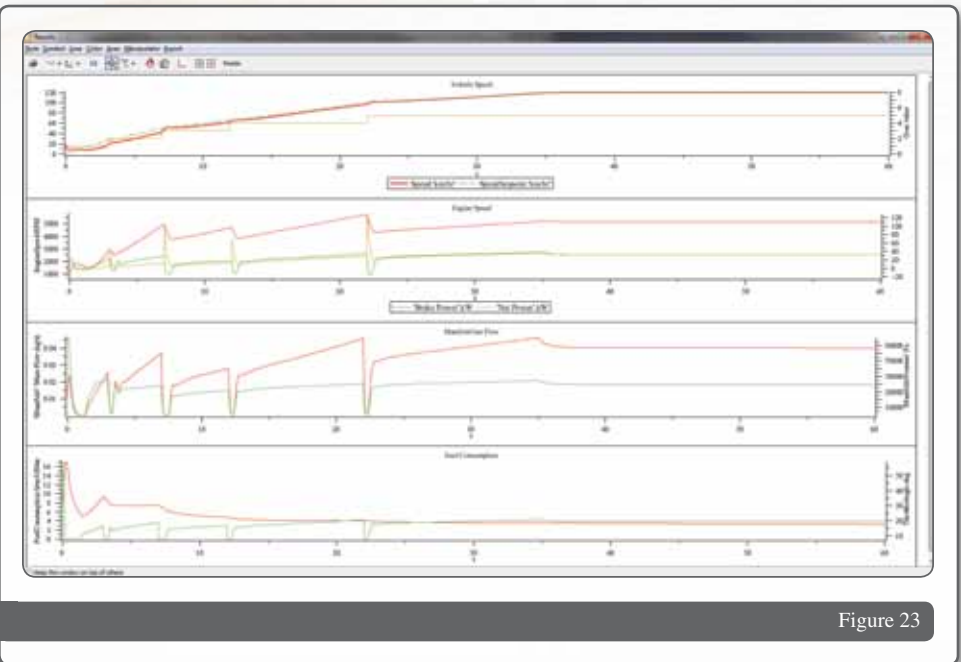


Figure 23



Figure 24

Simple Engine Model

ZF 4HP22 4-speed automatic gearbox

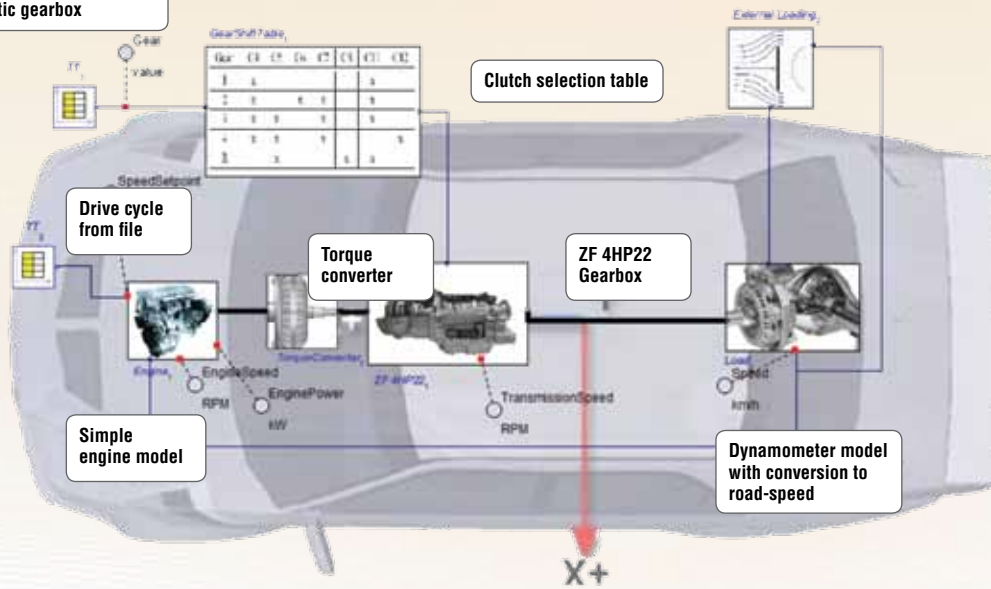
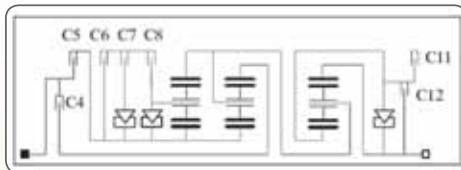
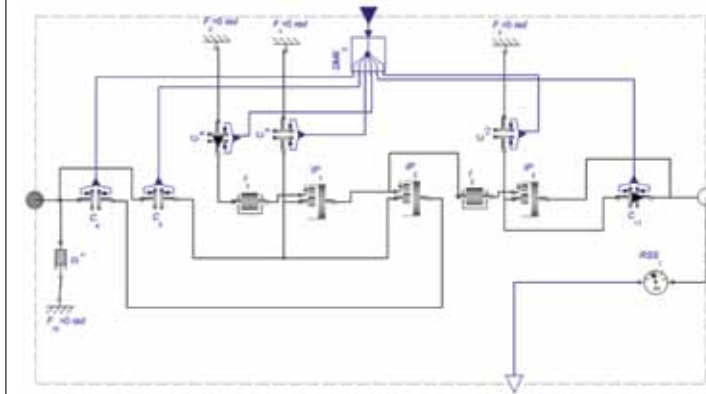


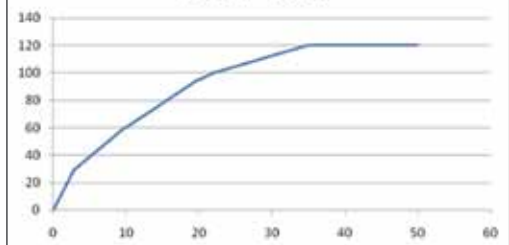
Figure 25



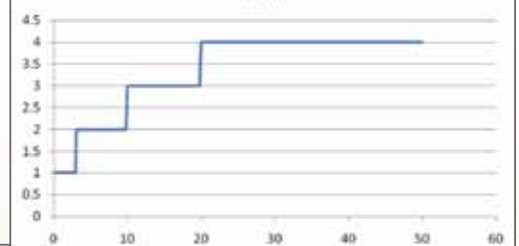
Gear	C4	C5	C6	C7	C8	C11	C12
1	x					x	
2	x		x	x		x	
3	x	x		x		x	
4	x	x		x			x
R		x			x	x	

Figure 26

Speed - km/hr



Gear



2.9	1	30
3	2	30
9.8	2	60
10	3	60
19.8	3	95
20	4	95
22	4	100
22	4	100
35	4	120
50	4	120

Figure 27

Ravigneaux 4-speed Transmission

This example models a Ravigneaux automatic transmission coupled to the simple controlled torque engine model via a torque converter.

This transmission model is based on the Ravigneaux gear configuration, which provides four gear ratios. Gear ratios are selected by engaging and disengaging clutches in a specific pattern, shown in the clutch selection table, and provided in a lookup file.

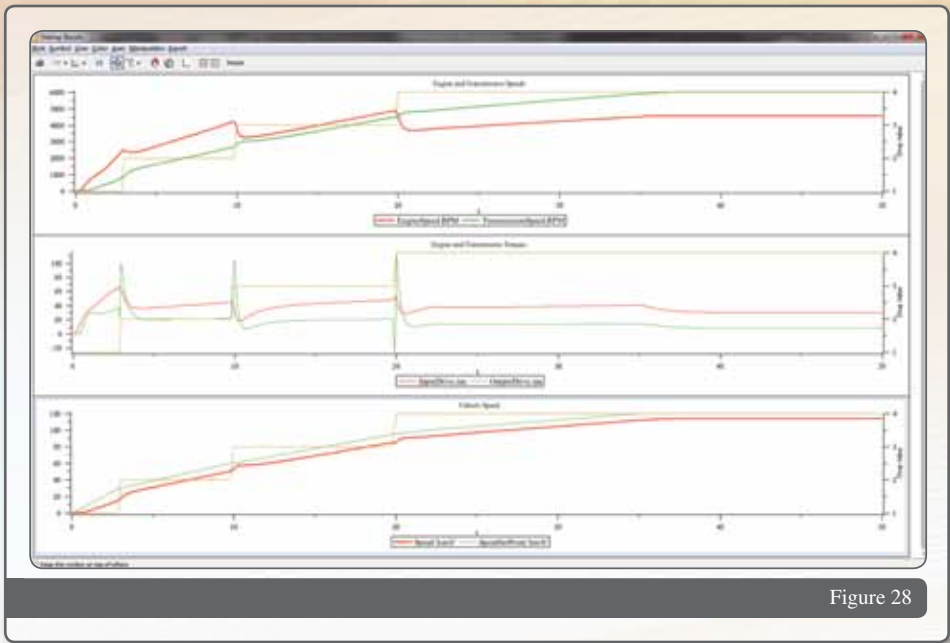
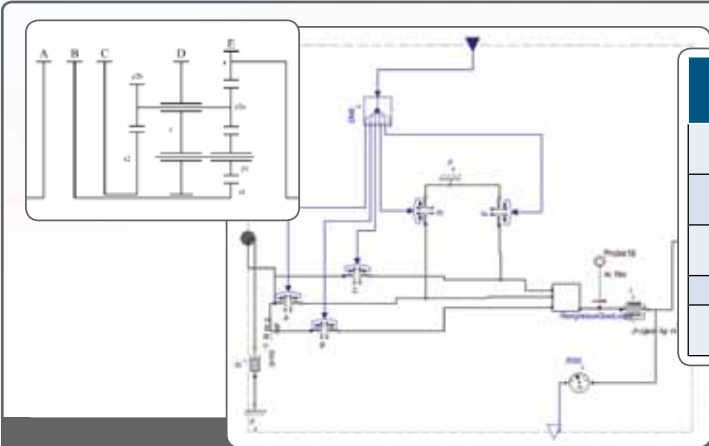


Figure 28



Gear	Clutch States					Ratio Expression	zR=150 zLS=75 zSS=50
	A	B	C	D	E		
R	0	0	1	1	0	$-\frac{zR}{zLS}$	-2
1	0	1	0	1	0	$\frac{zR}{zSS}$	3
2	0	1	0	0	1	$\frac{zR}{zSS} \cdot \frac{(zSS + zLS)}{(zLS + zR)}$	1.67
3	1	1	0	0	0	1	1
4	1	0	0	0	1	$\frac{zR}{(zLS + zR)}$	0.67

Figure 29

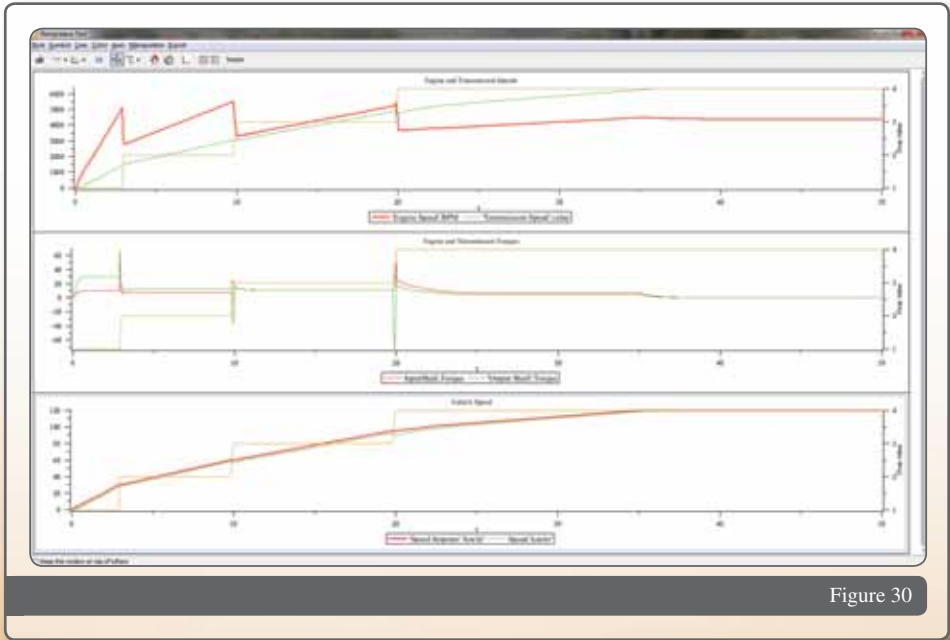


Figure 30

Vehicle Power Train

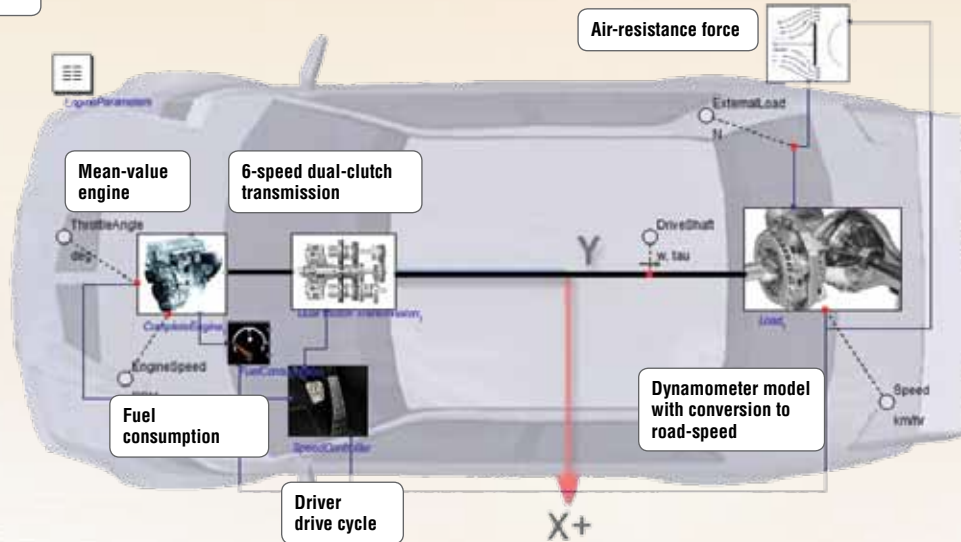


Figure 31

6-speed Dual-Clutch Transmission

Dual clutch transmissions are becoming an increasingly popular, more efficient alternative to planetary automatic transmissions. It is based on the simpler manual transmission concept but with alternating gears arranged on two shafts (odd numbers on one, even on the other) that are attached to separate clutches. Gear selection is effected through a mechanical selector, similar to the manual selector, applied while the shaft is unloaded, then by engaging the appropriate clutch. The result is an almost seamless shift. Not only is the mechanical system significantly simpler, it does not require a hydraulic coupling to the engine, and is therefore more fuel-efficient.

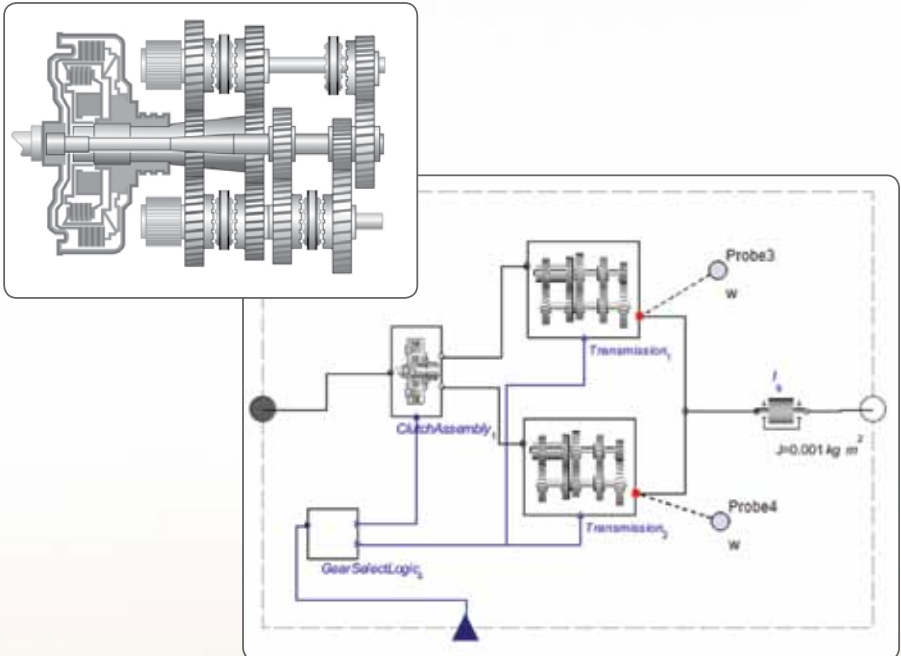


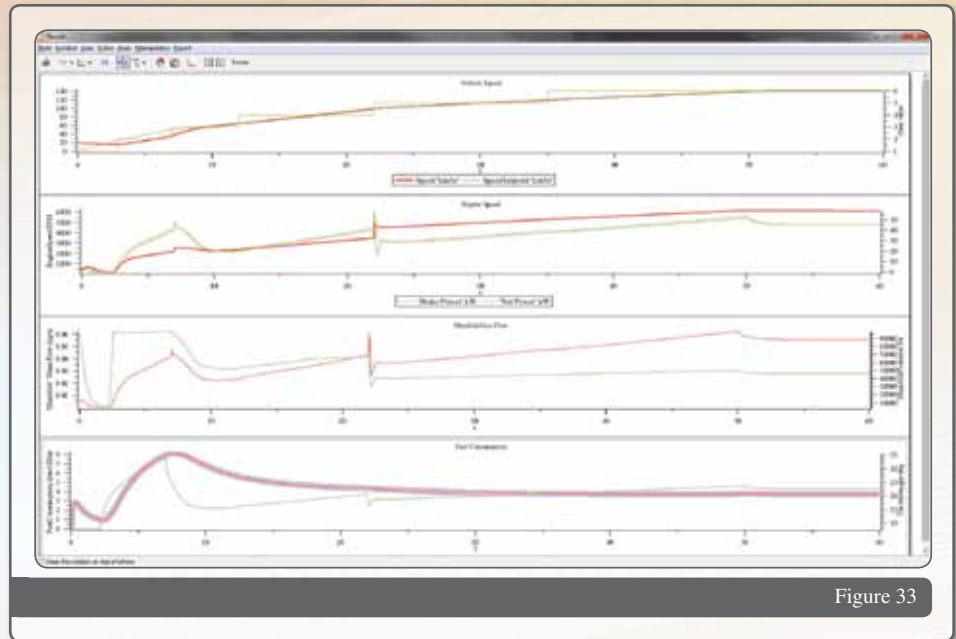
Figure 33

This example uses the mean-value engine model to drive the transmission.

The model for this 6-speed configuration is made of two manual transmissions with three gears each, with a clutch attached to each. The output from the two transmissions is connected to the same output shaft.

With this configuration, most of the complexity is in the controller. In this model, the selector logic for the manual transmission is extended to engage and disengage the required clutch, depending on the selected gear being odd or even.

The results show the vehicle accelerating through the 6 gears with very little disturbance during gear shifting, as expected.



Conclusion

The MapleSim Driveline Component Library described in this document is a very comprehensive collection that provides most of the fundamental components needed to build and test complex transmission models. The acausal model representation allows you to drag and connect for rapid model development. The open structure of the components makes it very easy to modify the shipped components to suit your specific requirements to increase the model fidelity. Even if a specific

transmission is not available in the library, building blocks are available which allow you to create your own with very little effort. Furthermore, the open structure and intuitive energy-loss components allow you to include power loss data as lookup tables, and configure them so that they best reflect the way in which the loss data was acquired.

MapleSim, with the addition of the MapleSim Driveline Component Library, provides the most flexible transmission

modeling environment available, allowing you to mix the best of physical models and empirical data to maximize model fidelity, optimize your designs and improve overall vehicle fuel-efficiency.

To learn more about MapleSim and the MapleSim Driveline Component Library, visit www.maplesim.com.

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