User Guide for the 30NOV2017 Version

of the

ICV Power Train Model

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Acronyms

ICV	Internal combustion vehicle
G/D	Gasoline/Diesel
Hyzem	An unofficial European transient driving cycle
NEDC	New European driving cycle
FTP	Federal test procedure (U.S. city driving)
HWFET	Highway fuel economy test (U.S. highway driving)
WLTP	Worldwide harmonized light vehicles test procedure
BSFC	Brake specific fuel consumption
RPM	Revolutions per minute
N/V	Engine rotational speed over vehicle speed (in RPM/mph)

Variables Names

M	Vehicle mass (in kg)
A_F	Frontal area of vehicle (in m^2)
c_D	Aerodynamic drag coefficient
f_R	Rolling resistance coefficient
ε	Rotary inertia fraction
g	Acceleration due to gravity (in m/s^2)
ρ	Density of air (in kg/m^3)
$F_T(t_i)$	Force demand at tire patch at time t_i (in N)
$v(t_i)$	Vehicle speed at time t_i (in m/s)
η_Y	Energy conversion efficiency of device Y
ED_T	Energy demand of a given driving cycle at tire patch (in MJ/km)
$T_X(t_i)$	Torque demand at point X in the drivetrain at time t_i (in Nm)
$\Omega_X(t_i)$	Rotational speed demand at point X in the drivetrain at time t_i (in rad/s)
FC	Fuel consumption of a specified vehicle and driving cycle (in liter/km)
$ALFC$	Accessory load fuel consumption of a specified vehicle and driving cycle
TFC	Total fuel consumption ($TFC = FC + ALFC$)

1 How to use the Model

1.1 Enter vehicle specifications and driving cycle

The model simulates moving a specified vehicle through a specified driving cycle. The calculations behind the simulations can be found in Section 2 of this User Guide (How the model calculates fuel economy). The role of each Excel spreadsheet is explained in Section 3. Only the ‘Input Data’ spreadsheet is required to use the Power Train Model.

All cells shaded blue on the ‘Input Data’ spreadsheet are input parameters. Figure 1 shows a screenshot of the vehicle specification sections of the ‘Input Data’ spreadsheet.

Inputs						
Vehicle Parameters						
Test Mass	*kg*	1240	Rotary inertia fraction		-	0.000
Rolling resistance coeff.	-	0.008	Accessory load		*W*	0
Acceleration due to gravit	m/s^2	9.810				
Frontal area	m^2	2.240				
Drag coefficient	-	0.300				
Air density	kg/m^3	1.225				
Spin loss coefficient	*N/(m/s)*	0.000				
DriveTrain Parameters						
Tire rolling radius	*m*	0.33				
Final drive						
Final drive ratio	-	3.50				
Final drive efficiency	-	0.95				
Transmission						
Gear	-	1	2	3	4	5
Gear ratio	-	4.00	2.60	1.69	1.10	0.71
Gear efficiency	-	0.95	0.95	0.95	0.95	0.95
Shift duration	*sec*	0.75				
Torque converter						
Stall Torque Ratio (STR)	*Tout/Tin*	2.00				
Extension (EXT)	$\Omega o/\Omega i$	0.90				
N/V (calculated)	*RPM/mph*	181.10	117.72	76.52	49.74	32.33
Engine						
Select Engine		G 1.4L 125 R4	Click to update to selected engine			
Torque Scaling Factor	$T_{RESIZED}/T_{BASE}$	1.00				
Fuel density gasoline	*gm/liter*	730.00				
Fuel density diesel	*gm/liter*	835.00				
Idle fuel consumption gasoli	*l/s/liter disp*	1.00E-04				
Idle fuel consumption diesel	*l/s/liter disp*	1.00E-04				

Figure 1: Screenshot of the vehicle specification sections of the ‘Input Data’ spreadsheet

The spreadsheet is pre-populated with input data, which need to be changed to the values the user would like to use for the simulations. Some values are more likely to change than others.

Unlikely to change are *acceleration due to gravity* and *air density*, which are standard physical values. The user may also chose to use the pre-populated parameter settings for the *final drive*, the *transmission* and the *torque converter*. Those settings should only be changed if the user has values that are known to be a better fit for the specified vehicle than the preselected ones. The same is true for *fuel density* and *idle fuel consumption*. Note that the idle fuel consumption value is per liter engine displacement and is scaled with the displacement of the selected engine.

The input parameters that are most likely to be changed by the user are:

Test (vehicle) mass, *rolling resistance coefficient*, *rotary inertia fraction*, *frontal area*, *drag coefficient*, *spin loss coefficient*, and *tire rolling radius*. These seven parameters are required to calculate the tractive force demand at the tire patch of the vehicle and convert it to axle torque demand.

The rotary inertia fraction expresses the rotational inertias from tires, wheels, and driveline components as a fraction of the translational inertia, which is the entire mass of the vehicle. A typical value for the rotary inertia fraction is 0.05.

The spin loss coefficient is determined empirically and quantifies the viscous forces generated in the drivetrain, which create a resistance force proportional to vehicle speed (rolling resistance is independent of vehicle speed; aerodynamic resistance is quadratic in vehicle speed). This parameter should be set to zero if the actual value is unknown.

The fact that the engine has to power not just the vehicle's motion, but also accessory load is modelled through the *accessory load* parameter. Typical values for the accessory load parameter are 500 W or 750 W.

Finally, an engine map and a driving cycle need to be selected. This is done in the *select engine* and *select schedule* cells, which both provide drop down menus showing all currently available engine maps and driving cycles.

If none of the available engine maps are a good match for the desired simulation, the map closest to the desired engine should be selected and then resized using the *torque scaling factor*. The *torque scaling factor* simulates a change in the engine displacement, which in turn affects maximum engine torque and power. The resulting maximum engine torque and power is reported (in orange) under the Engine section on the 'Input Data' spreadsheet. The Section 2.3 of this user guide explains why engine resizing can be modeled by scaling the torque axis on an engine map by a constant factor.

It is very important to click the 'update selected engine' button each time a different engine map is selected or a different torque scaling factor is entered. Otherwise the model results are incorrect.

The torque scaling factor can be chosen to yield a desired vehicle specification, such as a desired 0-60 mph acceleration time or a desired maximum engine torque or power. This can be done using Excel's goal seek function which can be found under the Data Validation icon on Excel's Data tab. See Section 1.3 below for more info on the use of the goal seek function.

1.2 Interpret results

Each time an input parameter value is changed or a different driving cycle is selected from the drop down menu, Excel instantly recalculates the simulation results.

After selecting a different engine map from the drop down menu or changing the torque scaling factor, the 'update selected engine' button has to be clicked in order to obtain correct results.

All simulation results are displayed in orange, together with some info on the modeled engine. The most important value is the *total fuel consumption*, which is the sum of the *fuel consumption for driving* and the *fuel consumption for accessories*. The latter will be zero if *accessory load* is set to zero.

Also of interest is the *acceleration time 0-60 mph calculated*, which is determined in a separate simulation.

The four model outputs given in the *Drivetrain Capability* section allow the model user to determine if the vehicle specifications are matched with a realistic engine model. If *6% gradeability*, *27% gradeability*, *0-15 mph launch time*, and *engine speed at 70 mph highway cruising* are unrealistic, the user may want to select a different engine or rescale the selected one.

The *Engine* section lists a number of engine specifications, which are also designed to help the user select a suitable engine model.

1.3 Conduct sensitivity and scenario analysis

Sensitivity and scenario analysis can be conducted simply by changing input parameter values and comparing old and new results.

Again, the ‘update selected engine’ button has to be clicked after changing the engine map or the torque scaling factor.

Probably of highest interest to many users is the sensitivity of the fuel economy with regard to vehicle mass. This sensitivity is sometimes called *Fuel Reduction Value* and simply calculated as the difference between old and new fuel economy divided by the change in vehicle mass. It is typically expressed in liters per 100km and 100kg mass reduction.

Vehicle mass reduction will not only reduce the fuel economy, but also the 0-60 mph acceleration time. One scenario of high interest is thus vehicle mass reduction plus resizing of the engine in order to keep the 0-60 mph acceleration time constant. This is done using Excel’s Goal Seek function which can be found under the What-if Analysis icon on the DATA tab (Figure 2).

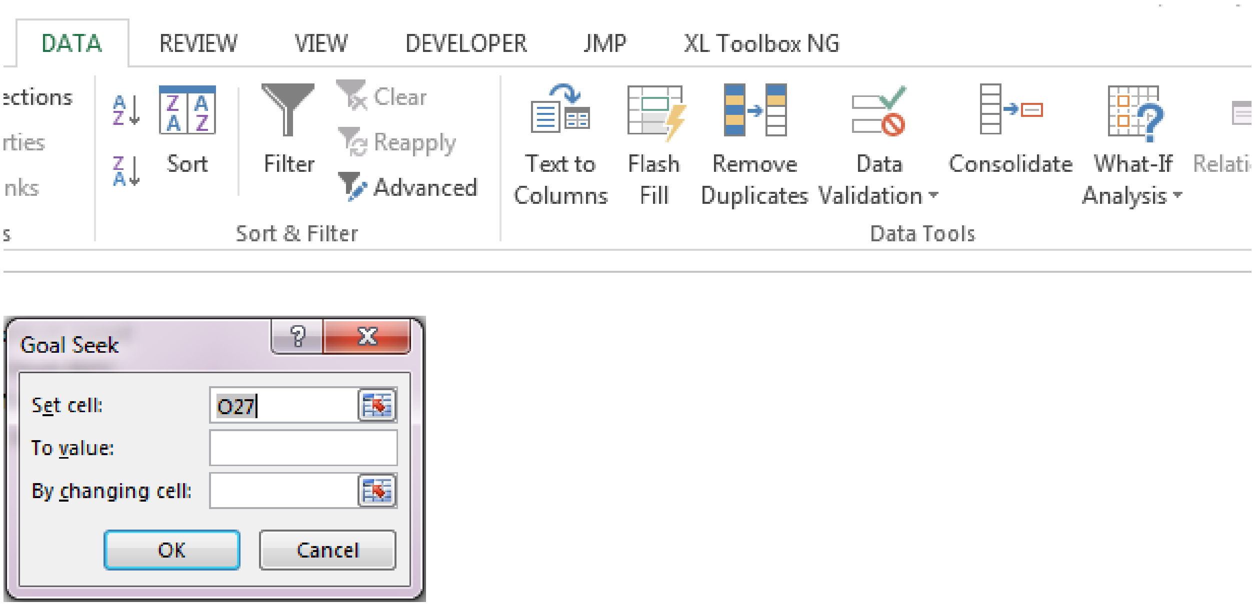

Figure 2: The Goal Seek function can be found under the What-if Analysis icon (DATA tab).

To resize the engine to keep 0-60 mph acceleration time constant, the user has to highlight the *acceleration time 0-60 mph calculated* cell (O27), open Goal Seek, enter the desired 0-60 mph acceleration time in the cell next to ‘To value:’, point the cell next to ‘By changing cell:’ to the *torque scaling factor*, and click the OK button. Goal Seek will find the torque scaling factor which yields the desired 0-60 mph acceleration time.

2 How the model calculates fuel consumption

Vehicle fuel demand is given in liters of fuel per 100km and calculated by moving a vehicle through a so-called driving cycle, which specifies vehicle velocity $v(t)$ (in meters per second) as a function of time t, typically given in time increments of one second t_i. The approach to power-train modeling used here is to calculate the net tractive force demand F_T at the vehicle's tire patch for each time increment t_i and then determine the operating point of the power train that provides the required force under realistic operating conditions. The operating point of the powertrain, in turn, determines the fuel demand of the internal combustion engine, called brake specific fuel consumption (BSFC) and given in gram per kWh. For a given driving cycle, the fuel demand of the vehicle is obtained simply by summing up the fuel demands of each time increment t_i and normalizing the result to 100 km.

Two objectives drove the selection of the modeling methods and choices. The first is to rely entirely on driving and powertrain physics and not use any engineering rules of thumb or approximations. The second is to obtain accurate results with a minimal number of vehicle and powertrain parameters. The latter objective aims at finding the sweet spot between model accuracy and modeling effort and complexity, a modeling approach sometimes called parsimonious.

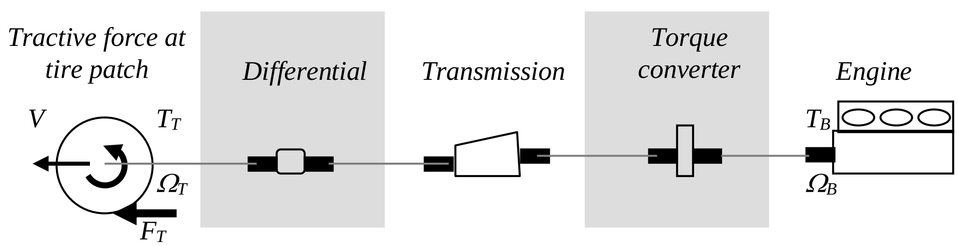

Figure 3: Overview of the ICV powertrain model

2.1 Force demand at tire patch and secondary loads

The first step is to calculate the net tractive force that is required at the tire patch during each time step in order to move the vehicle through the drive cycle. In addition to the driving cycle $v(t)$, the minimal set of input parameters required to calculate tractive force demand are mass M, frontal area A_F, and aerodynamic drag coefficient c_D of the vehicle, as well as the rolling resistance coefficient of the tires f_R. The force demand at time t_i due to rolling resistance is calculated as

$F_R(t_i) = Ma = Mgf_R$, with $g = 9.81\frac{m}{s^2}$ being the acceleration due to gravity. The force demand at time t_i due to aerodynamic resistance is calculated as $F_D(t_i) = \frac{1}{2}\rho c_D A_F v(t_i)^2$, with $\rho = 1.225\frac{kg}{m^3}$ being the density of air. The force demand at time t_i due to acceleration/deceleration is calculated as $F_A(t_i) = Ma = M \cdot \left(\frac{v(t_i)-v(t_{i-1})}{t_i-t_{i-1}}\right)$. Net force demand at the tire patch is calculated as $F_T(t_i) = F_R(t_i) + F_D(t_i) + F_A(t_i)$ and can be positive or negative, since the negative force of deceleration can be larger than the sum of the always positive rolling resistance and aerodynamic drag forces. A negative value of F_T indicates frictional or regenerative braking.

There are two secondary loads in addition to the primary tractive force demand, which are included in the powertrain model. They are the rotary inertia of rotating vehicle components and the spin loss of the drive train. As the vehicle moves forward, rotational inertias such as tires, wheels, and driveline components must also be rotationally accelerated. This rotary inertia can be described as an additional term of the translational inertia, i.e. $F_R = M(1+\varepsilon)a$, where $M\varepsilon$ is the effective additional inertia mass due to rotating components.

Spin loss is a resistance force proportional to vehicle speed. An empirical way to measure the forces resisting forward motion is to estimate the coefficients in equation $M\frac{dv}{dt} = A + Bv + Cv^2$ through coast down tests. A is identical with the rolling resistance force $A = F_R = Mgf_R$. C is due to aerodynamic drag and thus calculated as $C = \frac{1}{2}\rho c_D A_F$. Spin loss coefficient B is related to the viscous forces generated in the drivetrain and determined empirically.

The resulting net force required during time increment t_i in order to move a vehicle through driving cycle $v(t_i)$ is now calculated as $F_T(t_i) = Mgf_R + Bv(t_i) + \frac{1}{2}\rho c_D A_F v(t_i)^2 + M(1+\varepsilon)\frac{v(t_i)-v(t_{i-1})}{t_i-t_{i-1}}$. The final part in this first modeling step is to convert translational speed $v(t_i)$ (in meter per second) and force demand $F_T(t_i)$ (in Newton) into rotational tire speed $\Omega_T(t_i)$ (in rad per second) and axle torque demand $T_T(t_i)$ (in Newton meter) according to the equations $T_T = r \cdot F_T$ and $\Omega_T = v/r$, with r being the rolling radius of the tire.

An interesting and useful intermediate result is the total energy demand at the tire patch, which is calculated as $ED_T = \sum_i F_T(t_i) \cdot v(t_i)$ and given in MJ per km.

2.2 Torque demand at engine shaft

The next step is to model the drive train components between the tires and the engine. A minimal set of components that needs to be modeled is the differential, the transmission, and the torque converter. The model calculations follow the power train backwards, or from left to right in Figure 1. The differential and transmission gears are defined by their gear ratios and their torque/energy conversion efficiencies, which are used to convert the required torque and rotational speed output (in Nm and rad/s) into the corresponding torque and rotational speed input. Required torque input into the differential is thus calculated as $T_{D-in} = T_T/(\eta_D \cdot R_D)$, with η_D being the energy/torque conversion efficiency, R_D being the gear ratio of the differential, and $T_{D-out} = T_T$. Speed input into the differential is calculated as $\Omega_{D-in} = R_D \cdot \Omega_{D-out} = R_D \cdot \Omega_T$.

The function of the transmission is to convert the required output torque and speed to corresponding values of engine torque and speed that allow efficient and smooth operation of the engine. For each gear, required torque and speed input to the transmission are calculated in the same way, i.e. $T^n_{Tr-in} = T_{D-in}/(\eta_n \cdot R_n)$ and $\Omega^n_{Tr-in} = R_n \cdot \Omega_{D-in}$, with η_n being the energy/torque conversion efficiency of gear n, R_n being the ratio of gear n, $T_{D-in} = T^n_{Tr-out}$, and $\Omega_{D-in} = \Omega^n_{Tr-out}$.

The function of the torque converter is to allow non-zero engine speed when the vehicle is at rest and to match torque needs at low vehicle speeds. A simple, yet reasonable model of the torque converter is to assume that the torque output over input ratio is a linear function of the speed output over input ratio, i.e. $\frac{T_{Tr-in}}{T_{TC-in}} = -\frac{STR}{EXT}\frac{\Omega_{Tr-in}}{\Omega_{TC-in}} + STR + 1$. Here STR is the stall torque ratio and EXT (called extension) is the point at which the lockup clutch directly connects engine and transmission without slippage, i.e. $\frac{T_{Tr-in}}{T_{TC-in}} = 1\ for\ \frac{\Omega_{Tr-in}}{\Omega_{TC-in}} \geq EXT$. By far the largest torque converter slippage occurs in first gear. Therefore slippage is only modeled there and not in any of the higher gears. This means that in the vast majority of time steps $T_{TC-in} = T_{Tr-in}$.

For each time step t_i the model needs to determine which gear the car is operated in. To do that the brake torque $T_B(t_i) = T_{TC-in}(t_i)$ and engine speed $\Omega_B(t_i) = \Omega_{TC-in}(t_i)$ required at each time step to move the vehicle through the driving cycle is calculated for every gear. In other words, for each time step t_i n pairs of required brake torque $T_B(t_i)$ and engine speed $\Omega_B(t_i)$ are calculated by the powertrain model.

2.3 Fuel demand

The final step of the powertrain model is to convert the torque demand at the engine shaft into fuel demand. This step is complicated by the fact that brake specific fuel consumption (BSFC), i.e. fuel consumption rate per power output, is a complex function of engine torque and engine speed. The relationship has to be determined empirically, through engine tests, and the resulting data is stored and visualized in so-called engine maps. BSFC is essentially the energy conversion efficiency of the engine at a given operating point, i.e. torque and speed, and typically given in g/kWh. Simplified power train models used in environmental assessments typically use a constant BSFC, or other simplifications, even though the conversion efficiency of a typical engine varies from single digits to close to 40%.

For each time step t_i and gear the power train model looks up the BSFC that matches the required brake torque and engine speed. The engine maps in the power train model are data tables with 10 Nm torque and 100 rpm speed intervals. To increase model precision linear interpolation is used to calculate the BSFC of each engine operating point. It is possible that, for some time steps of the driving cycle, certain gears would require brake torque and engine speed combinations that are not feasible with the chosen engine map. For each time step, the power train model needs to select one of the feasible gears. Many different gear shifting logics could be implemented. In the current version, the power train model simply chooses the gear with the lowest BSCF. For the time steps in which the net force demand $F_T(t_i)$ is zero or negative, idle fuel consumption is selected, which is another data input given in liter gasoline or diesel per second and liter engine displacement. The last step is to calculate the fuel consumption during each time step as $FC(t_i) = BSFC(t_i) \cdot \Omega_B(t_i) \cdot T_B(t_i) \cdot \rho_{fuel}$, with ρ_{fuel} being the density of the used fuel in grams per liter, which is another data input to the model. The fuel economy for the specified vehicle and driving cycle, without accessory load, is now calculated as $FC = \sum_i FC(t_i)/(0.01 \cdot LDC)$, with $LDC = \sum_i v(t_i)/1{,}000$ being the length of the driving cycle in km. Multiplying the fuel economy with the energy density of the fuel yields the energy demand ED for the specified vehicle and driving cycle.

An additional source of fuel demand is accessory load AL, which is also a data input to the model and given in Watt of mechanical power demand. The additional fuel demand due to AL is calculated as $ALFC(t_i) = BSFC(t_i) \cdot AL \cdot \rho_{fuel}$. Total fuel consumption including accessory load is $TFC = \sum_i \big(FC(t_i) + ALFC(t_i)\big)/(0.01 \cdot LDC)$. FC and TFC are both given in liters per 100 km.

2.4 Vehicle performance and engine resizing

Comparative environmental assessments of vehicles need to make sure that functionally equivalent cars are compared. One pertinent example is that, all other things being equal, the performance of a vehicle will increase when its mass is reduced. A common approach to reestablishing functional equivalence is to downsize the engine of the mass-reduced vehicle, so that it has the same 0-60 miles per hour (mph) acceleration as the baseline car.

To implement such engine resizing, the power train model calculates the 0-60 mph acceleration time for the vehicle specified by the model user. It does so by calculating the time intervals it takes to accelerate the vehicle by 1 mph increments. For each speed increment, $x\ mph \rightarrow x + 1\ mph$, the model selects the gear that provides the maximum torque, converts this engine torque into force at the tire patch, and uses the net force demand equation to calculate the time it takes to increase vehicle speed by one mile. The time it takes to accelerate from 0 mph to 60 mph is simply the sum of the 60 time increments. The model also accounts for torque converter slip in first gear, tire slip beyond a set maximum force, and the time it takes to shift gear.

The resizing of the engine is modeled using a torque scaling factor, $T_{resized}/T_{base}$. This approach takes advantage of the fact that engine torque is directly proportional to the area of the piston heads, i.e. $T_{resized}/T_{base} = A_{resized}/A_{base}$, given that all other engine characteristics, such as number of cylinders, stroke, thermal, mechanical, and volumetric efficiencies remain the same. On the other hand, changing the area of the piston heads has no impact on engine speed and thus BSFC. As a result, engine resizing can be modeled by taking an engine map and scaling the torque axis be a constant factor, while leaving everything else the same. In the power train model, all engine maps can be resized manually.

The process of engine resizing after vehicle mass reduction to achieve equal performance is as follows: Enter all input data for the baseline vehicle and note the calculated 0-60 mph acceleration time. Reduce vehicle mass input data; the calculated 0-60 mph time will decrease as a result. Use the Excel goal seek function to set the 0-60 mph time back to the baseline value by changing the torque scaling factor, i.e. simulating a downsizing of the engine (see Figure 2). The result is a mass-reduced vehicle with the same 0-60 mph acceleration as the baseline vehicle.

3 Description of the additional spreadsheets

3.1 Selected Schedule

This spreadsheet contains all driving cycles which are available for simulation. All driving cycles are given as second by second velocity profiles $v(t)$. The velocity data are available in the original units, e.g. mph and kmh, and also in meters per second. The spreadsheet picks the pertinent vehicle specifications and the driving cycle that have been selected by the user and displays the velocity data in column B of the spreadsheet. It then calculates the net force demand at the tire patch for each second and shows the data in column D of the spreadsheet. Integrating over the velocity profile yields the total distance covered by the selected driving cycle (shown in cell C7). Integrating over the net force demand yields the total energy required at the tire patch in order to move the specified vehicle through the selected driving cycle. The ratio of those two values yields the energy demand at the tire patch in MJ per km (shown in cell E7).

3.2 Selected Map

This spreadsheet contains the engine map that has been selected by the user. The engine map is given as a data array that shows BSFC (in g/KWh) as function of engine speed (in rpm) and engine torque (in Nm). Engine speed is given in 100 rpm increments and engine torque in 10 Nm increments. All speed-torque combinations that are not possible with the selected engine are set to (an arbitrary and impossible) 10,000 and ignored by the simulation. In addition to the engine map data, the spreadsheet also contains idle fuel consumption, a maximum torque curve, a basic engine description, and the source of the engine map.

3.3 Fuel Cons Calc-Min bsfc

This spreadsheet converts vehicle speed and net force demand at the tire patch into engine speed and torque and then looks up the corresponding BSFC from the engine map on the 'Selected Map' spreadsheet. It does this for each second of the driving cycle, so each row after row 28 contains identical calculations, just for a different time increment of the driving cycle. The calculations are described in Sections 2.2 and 2.3 of this user guide. In summary, the calculations follow the drivetrain backwards from the tire patch to the engine (see Figure 3 on page 5), going through differential, transmission, and torque converter. The differential is characterized by its drive ratio and energy loss. Each gear is characterized by its gear ratio and energy loss. The torque converter is specified through its stall torque ratio and extension. Torque converter slip is only modeled for first gear.

On important modeling decision is to determine which gear the vehicle is in during each second of the driving cycle, taking into account that some gears may require engine speed and torque combinations that the specified engine cannot deliver. Many different gear shifting logics could be implemented. In the current version, the power train model simply chooses the gear with the lowest BSCF.

For each second of the driving cycle the selected gear is shown in column AQ; the resulting required engine speed in column AR, and the required engine torque in column AS. The resulting fuel consumption for each second is calculated in column AT. The simulation also checks and reports how many times the required torque is not possible with the selected engine. Cell AW25 calculates the total fuel consumption for the entire driving cycle by simply summing over all values in row AW. Dividing this value by the length of the driving cycle yields the fuel economy (in liters/100km). This value is reported in cell AX25 and also forwarded to the 'Input Data' spreadsheet. Fuel demand due to accessory load is calculated in row AZ.

3.4 Accel Perf Calculations

This spreadsheet contains the simulation that calculates the 0-15 and 0-60 mph acceleration times. The calculations are described in Section 2.4 of this user guide. Both acceleration times are forwarded to the 'Input Data' spreadsheet.

3.5 Gradeability Calculations

This spreadsheet contains the gradeability calculations. The two gradeability requirements are 6% at 65 mph (in fifth gear) and 27% at 5 mph (in first gear). For both conditions the engine torque demand is calculated and compared to the maximum available torque at the required engine speed. The available-demanded torque ratios are forwarded to the 'Input Data' spreadsheet.

3.6 All other spreadsheets

Each spreadsheet contains engine map data, engine description, and data source. The spreadsheet content of the selected engine is copied to the 'Selected Map' spreadsheet.