Pre-Project Report

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Abstract

The purpose of the project is to model and design powertrain for a PHEV and to that extent; it involves finding the power required and energy consumption for a glider vehicle, a conventional vehicle and a full electric vehicle and sizing components optimally. Components like engine, motor, battery pack are modelled individually then combined together as a complete powertrain.

Part I

A vehicle in itself is a very complex system and to model its energy consumption behavior, one treats it to be an object that needs to overcome resistances in a straight motion and the force that is thus required is called traction force and this type of model is known as longitudinal vehicle model.

$$\boldsymbol{F_{tr}} = \boldsymbol{F_{roll}} + \boldsymbol{F_{aero}} + \boldsymbol{F_{hill}} + \boldsymbol{F_{acc}}$$

Thus the energy required for a glider vehicle (see Table I) was estimated for EcoCAR 4-Cycle (see Fig. 1 to 5), which aims to cover all aspects of vehicle driving like city and highway driving, rapid accelerations and rapid braking, etc, as best as possible in a weighted sum of four different cycles.

Table 1. Glider Vehicle Specifications

Vehicle equivalent test weight including 2 people	1500 kg
Gross Vehicle Weight Rating	2000 kg
Drag Coefficient*Area	0.75 m^2
Coefficient of Rolling Resistance	0.009

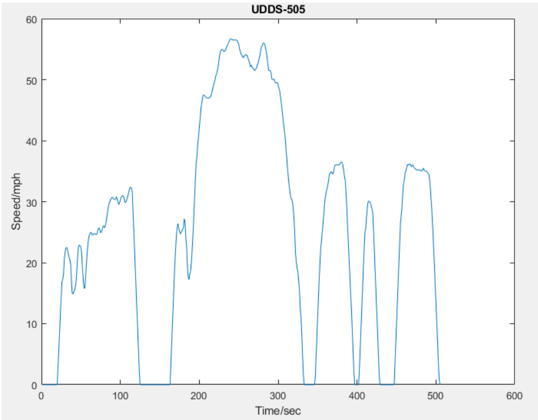

Figure 1. UDDS 505

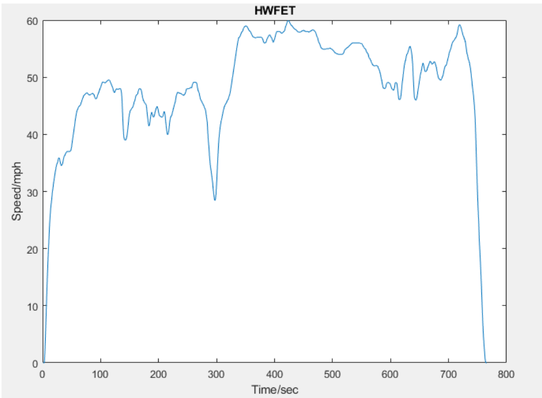

Figure 2. HWFET

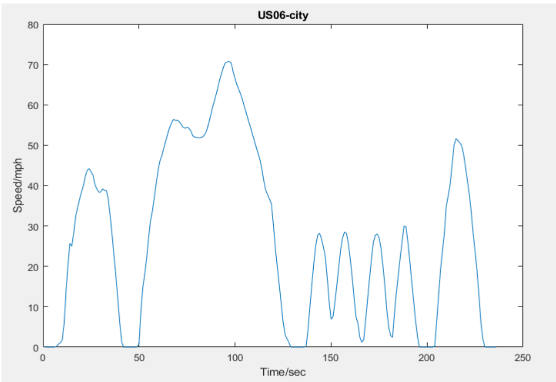

Figure 3. US06 City

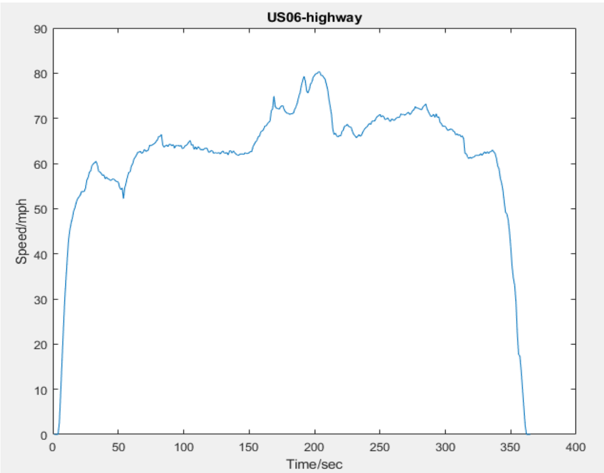

Figure 4. US06 Highway

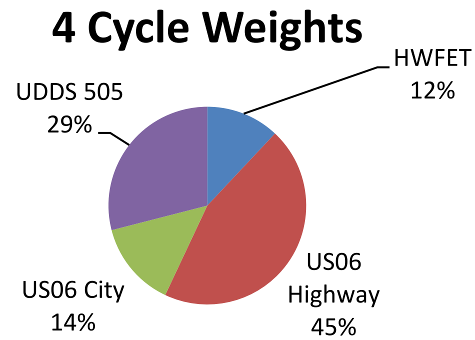

Figure 5. The different weights are used to account for the significance of each drive cycle on the 4 Cycle figure as a whole

The computational process for finding various ‘at the wheels’ results is summed up in the flowchart in Figure 7. The essence is to calculate tractive effort in a discretized time step of a given drive schedule. Although here, the time step taken was of 1 second due to the availability of drive schedules in such format, time steps should be as small as possible to more accurately mimic actual behavior in models that capture the dynamics of vehicle more accurately. The results are summed up in Figure 8.

Drive_Cycle	Max_Velocity_kph	Avg_Velocity_kph	Cycle_Time_s	Cycle_Distance_km
'UDDS 505'	25.347	11.444	505	5.7792
'HWFET'	26.778	21.549	766	16.507
'US06_city'	31.606	12.085	236	2.8521
'US06_highway'	35.897	27.494	365	10.035

Figure 6. Drive cycle properties

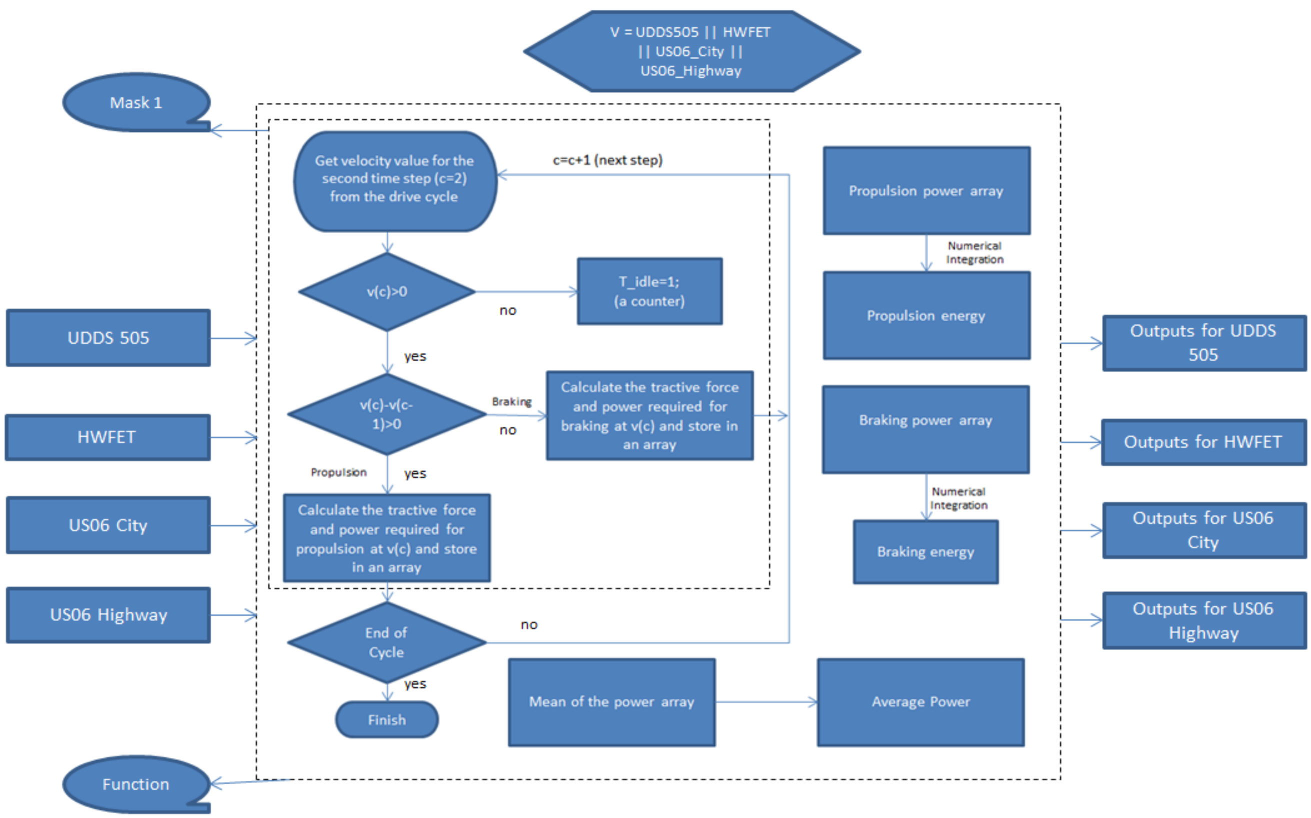

Figure 7. Flowchart depicting the computational processes involved in finding the ‘at the wheels’ results

At_the_wheels	udds505	hwfet	us06_city	us06_hw	weighted
'Propulsion Energy Wh/km'	122.63	93.822	260.5	148.32	150.03
'Braking Energy Wh/km'	54.258	32.734	144.68	45.773	60.516
'Net Energy Wh/km'	68.376	61.088	115.82	102.54	89.518
'Avg. Positive Power kW'	5.2323	7.7639	12.522	15.98	11.393
'Peak Power kW'	33.697	27.49	81.495	85.039	62.748
'Peak Tractive Force kN'	2.4111	2.2981	5.7731	4.7838	3.9359
'Idle Time %'	19.406	0.65274	15.254	1.9178	8.7047

Figure 8. 'At the Wheels' results

As an example of weighted calculation for propulsion energy requirements, the weights are used for the impact of each drive cycle:

$$(122.6 * 0.29) + (93.8 * 0.12) + (260.5 * 0.14) + (148.3 * 0.45) = 150.03\ Wh/km$$

It can be said that the average positive power and peak power requirements are greatest for US06 Highway due to its maximum velocity requirement and little deceleration. At the same time, its unit braking energy is higher than HWFET due to the braking happening at higher speeds. Overall, the propulsion and braking energy is greatest for US06 City due to its most aggressive accelerations and deceleration. Also the highway cycles have almost no idle time.

Although the results are only ballpark figures, they are great for a first estimation of powertrain delivery and energy storage requirements. For example, a conventional vehicle with similar specifications, for a required range of 300 km and an assumed average engine efficiency of 22% would require about 22 liters of gasoline with an energy consumption of 150 Wh/km since the braking energy will be lost as heat. Of course there are more details that can always be covered. Likewise, from the results, the engine can be sized in a first iteration for the peak power after accounting drivetrain power losses and accessory load.

The braking energy figure is that which is lost as friction heat in brake pads/discs in conventional vehicles but can be recuperated to an extent in xEVs. Also looking at the average power requirement and idle time figures, decision can be made on the degree of hybridization for engine start-stop and regeneration only or a full hybrid so that engine operates only at peak load requirement, depending on cost and fuel economy considerations.

The average power requirement of all the drive cycles is low and will result in low engine efficiencies. For example, the average power required for HWFET is 7.7 kW and average velocity of the drive cycle is 21.5 kph. For any midsize car, the engine speed will be around 3200 rpm. Considering a typical 2l engine, the load will be only about 1.43 bars i.e. at low end of the efficiency map and average efficiency of about 10-20% should be expected for the cycle.

Also calculated was the average power for acceleration and gradeability requirement (see Figure 9).

Performance Category	Vehicle Design Targets
Energy consumption, based on EcoCAR E&EC weighted 4-clcyle	Better than 370 Wh/km (600 Wh/mi)
GHG emissions, WTW based on EcoCAR E&EC weighted 4-clcyle	Less than 120 g of carbon dioxide equivalent (CO_2 eq)/km (200 g CO_2 eq/mi)
Range	Greater than 320 km (200 mi)
Maximum speed	Greater than 135 kph (85 mph)
Acceleration time of 0 to 97 kph (0 to 60 mph)	Less than 11 seconds
Highway gradeability (at gross vehicle weight rating [GVWR])	Greater than 3.5% grade at a constant 97 kph (60 mph) for 20 minutes

Figure 9. Vehicle design requirements

The average power required for an acceleration of 0-60 mph in 11 seconds was found using a 'smooth acceleration' velocity profile (see Fig. 10). Such a velocity profile is supposed to be representative of the actual velocity pattern when cars accelerate. It can be considered as a special drive cycle to find the average power required for a 0-60 mph in 11 seconds. Again, it is great to arrive at a ballpark figure that the powertrain should be capable of delivering (see Fig. 11).

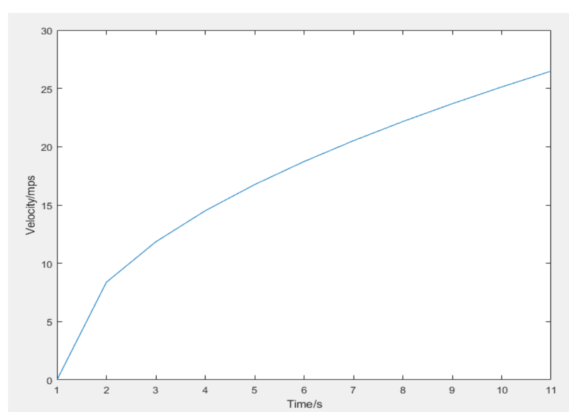

Figure 10. 'Smooth acceleration' profile

The computational process is same as mentioned in Figure 7. The average power for gradeability was calculated using the vehicle dynamics equation.

At_the_wheels_results	Values
'Average power required to meet minimum acceleration time kW'	61.218
'Average power required to climb 3.5% grade at 60mph at GVWR kW'	34.083

Figure 11. Average power for acceleration and gradeability requirement

It can be seen that the power requirement for acceleration will satisfy that for the gradeability. Thus, the peak power requirements of drive cycles and performance can be used to size the torque generator after accounting for auxiliaries and losses.

Part II

This part involves modeling an ICE powertrain with an engine model added to the glider vehicle model from first part for performance and energy consumption estimations. First, a baseline engine (see Fig. 12) is modelled using Willans model.

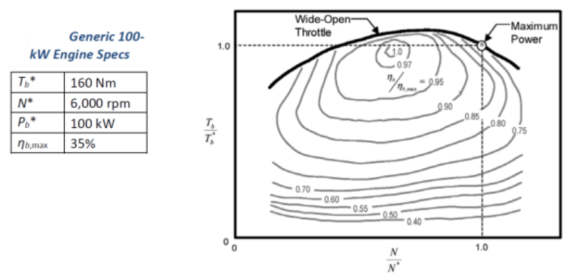

Figure 12. A representative gasoline engine map

The vehicle selected was 2018 Honda HR-V [4] which has similar engine specs as that of a generic 100 kW engine. The engine is modelled as a map using Willans model. Due to unavailability of an actual efficiency map, it was made sure that the map created using Willans model has the characteristics of a generic 100kW gasoline engine, assumption based on the premise that engines of similar size and type will have similar displacement and power. Even efficiency maps obtained from isolated engine dyno tests are steady state and do not capture the dynamic behavior of the engine [7]. The engine model here is an approximation of the map itself.

Engine Type	In-Line 4-Cylinder
Engine Block/Cylinder Head	Aluminum-Alloy
Displacement	1799 cc
Horsepower (SAE net)	141 @ 6500 rpm
Torque (SAE net)	127 lb-ft @ 4300 rpm
Redline	6700 rpm
Bore and Stroke	81 mm x 87.3 mm
Compression Ratio	10.6 : 1
Valve Train	16-Valve SOHC i-VTEC®

Figure 13. Engine specification of 2018 Honda HR-V [4]

Transmissions	
6-Speed Manual Transmission (6MT) Gear Ratios:	
1st:	**3.642**
2nd:	**1.885**
3rd:	**1.361**
4th:	**1.024**
5th:	**0.830**
6th:	**0.686**
Reverse:	**3.673**
Final Drive:	**4.705**

Figure 14. Transmission of 2018 Honda HR-V [4]

It has been experimentally validated in multiple literatures that the following simple relationship between mean fuel pressure and mean effective pressure approximates the real engine behavior astonishingly well:

$$p_{me} = e.p_{ma} - p_{mloss} \qquad (2)$$

The efficiency coefficient 'e' represents the thermodynamic properties of the engine (i.e., the deviations from a perfect conversion from chemical energy in the fuel to mechanical work), whereas the second part p_{mloss} incorporates the friction and gas-exchange losses both being functions of mean piston speed [1].

As such, both factors have general characteristics for a particular type of energy converter and hold for different scaled versions of that type. For a gasoline engine:

- 'e' has a parabolic form: can be attributed to large amount of heat losses at low speeds and bad combustion timing at high speeds; and values less than 1 typical of any thermodynamic efficiency
- 'ploss' which is representative of friction and pumping losses increases with speed

Note that both are a function of the engine speed and can be approximated as such (see Eqn. 3 and 4). Therefore, available plots [2] of e and p_{mloss} as a function of mean piston speed were used and all the parameters were tweaked with the attempt that various peak values, such as peak efficiency, maximum torque, and maximum engine speed, all match to some extent to the vendor provided efficiency map or in this case, the generic 'representative' map.

$$e = e_{00} + e_{01}.cm + e_{02}.cm^2 \qquad (3)$$

$$p_{mloss} = p_{loss0} + p_{loss1}.cm + p_{loss2}.cm^2 \qquad (4)$$

Since initially, only the efficiency values are available from an existing engine map, following equation can be used:

$$p_{me} = \frac{p_{mloss}(cm)}{\left(\frac{e(cm)}{\eta}\right) - 1} \qquad (5)$$

The efficiency map thus obtained from Willans model was tweaked by varying model coefficients to match the original map (see Fig. 14):

- Match the maximum piston speed
- Match the maximum efficiency
- Match the peak torque value
- Match general shape of contour lines

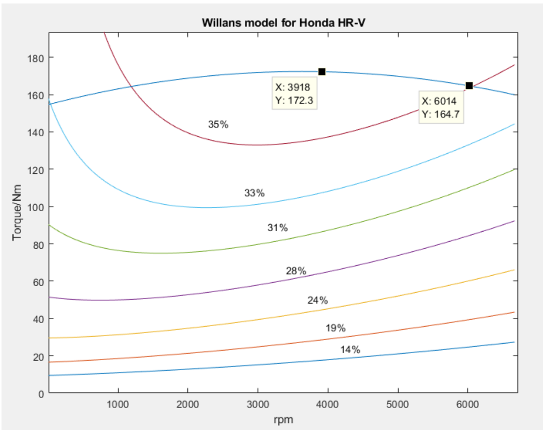

Figure 14. Efficiency map from Willans model of a Honda HR-V R18A engine has comparable characteristics of a generic map 100kW gasoline engine

Table 2 Willans model factors

	e	***ploss***
cm^2	-0.00019	0.0049;
cm	0.00999;	0.0926
1	0.361	1.0409

Note that using (2), a maximum value of mean fuel pressure can now be found. This can be explained as follows. The affine relation given by (2) is a simplification of a more general form:

$$p_{me} = e\left(m_a, \omega_e, \lambda, \zeta, x_{egr} \dots\right) p_{ma} - p_{mloss}(\omega_e, \vartheta_e, ..) \quad (6)$$

Using the following simplifications:

$$\frac{\partial e(m_a,\omega_e,\lambda,\zeta,x_{egr}\dots)}{\partial m_a} = 0 \quad (7)$$

$$\frac{\partial p_{mloss}(\omega_e,\vartheta_e,..)}{\partial m_a} = 0 \quad (8)$$

Equation (2) becomes affine in injected fuel mass (or p_{ma}) [1].

Hence, at given engine speed c_m at which mean effective pressure is maximum,

$$p_{ma\_max} = \frac{p_{me\_max}(cm) + p_{mloss}(c_m)}{e(c_m)} \quad (9)$$

In other words, it is assumed innately in the model that at any speed, maximum fuel mass is used to produce maximum torque (varying p_{ma_max}). This was used ($p_{ma\_max} = 32.8\ bar$) to find the WOT performance parameters.

The computational processes are summed up in Figure 15.

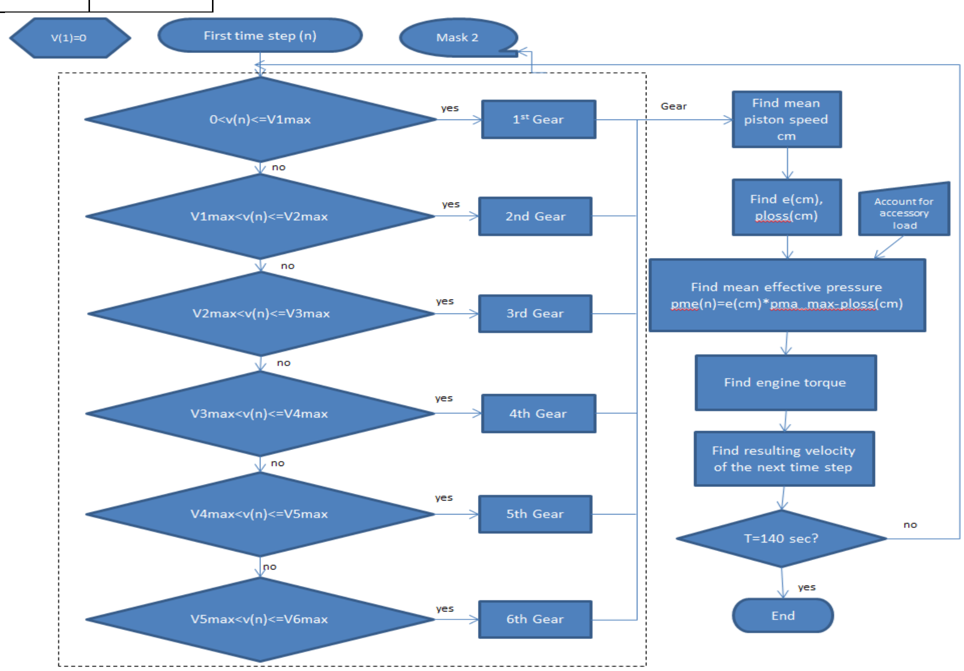

Figure 15. Flowchart for WOT performance of a conventional vehicle

Having the engine model equations, the mass of powertrain components, accessory load and driveline load was accounted for next.

The accessory load depends on engine speed (see Fig. 16) and for simplification; a single average value of loads of all accessories run by the engine (alternator, power steering pump, AC compressor, etc.) was used. Honda HR-V has EPAS (Electrical Power Assisted Steering) and thus lacks parasitic wastage from the engine due to pump. Hence, a continuous load of ($\approx 8\ kW,$ value at max engine speed) was assumed. Also, a driveline efficiency of 0.95 was assumed. The mass of engine and transmission was taken to be 101 kg and 66 kg respectively [5].

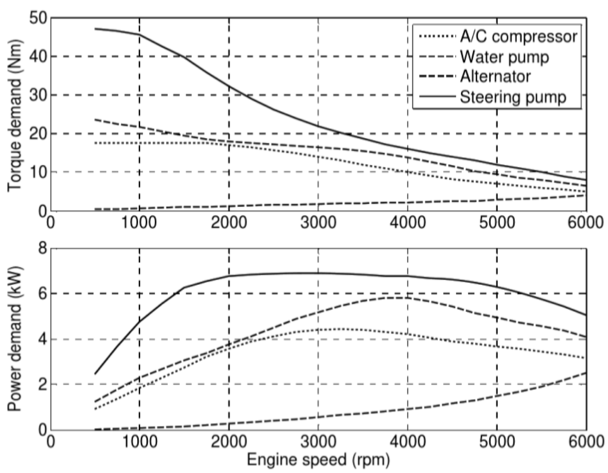

Figure 16. Typical accessory load [3]

The performance estimates are shown in Figures 15-17 and are comparable to the actual performance results (see Fig. 22). Note that in actual, there is an engine torque interruption during a shift which is ignored here for simplicity. Also, the 6th gear seems to be redundant in the model (see Fig. 18). This is due to the fact that actual engines operate between their idle speeds and redline but in the model, it operates from zero speed to is maximum speed for simplicity and thus has a wider velocity range that each gear covers.

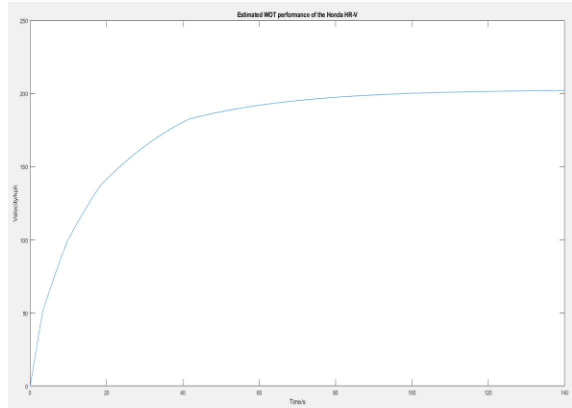
Figure 17. WOT performance

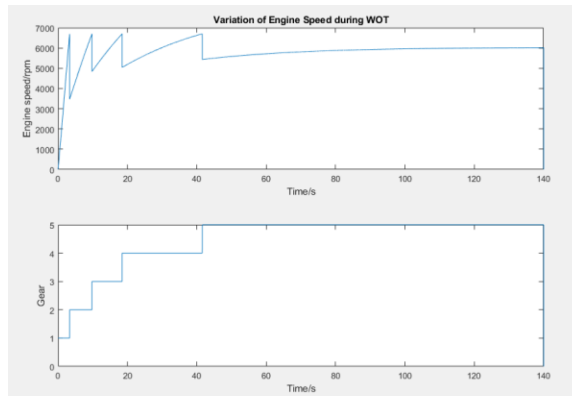

Figure 18. Variation of engine speed and gear shifts

Parameters	Values
'Test mass kg'	[1.6673e+03]
'Max Speed kph'	[202.0600]
'Acceleration 0-60 mph s'	[9.9600]
'Highway gradeability at 60mph at test mass %'	[21.2813]
'Powertrain sizing:'	' '
'Engine peak power kW'	[105]
'Estimated accessory load kW'	[8]
'Engine mass kg'	[101]
'Transmission mass kg'	[66.3000]
'Transmission gearing'	' '
'1st gear'	[3.6420]
'2nd gear'	[1.8850]
'3rd gear'	[1.3610]
'4th gear'	[1.0240]
'5th gear'	[0.8300]
'6th gear'	[0.6860]
'Reverse'	[3.6730]
'Final drive'	[4.7050]

Figure 19. Results of ICE powertrain sizing for the baseline model

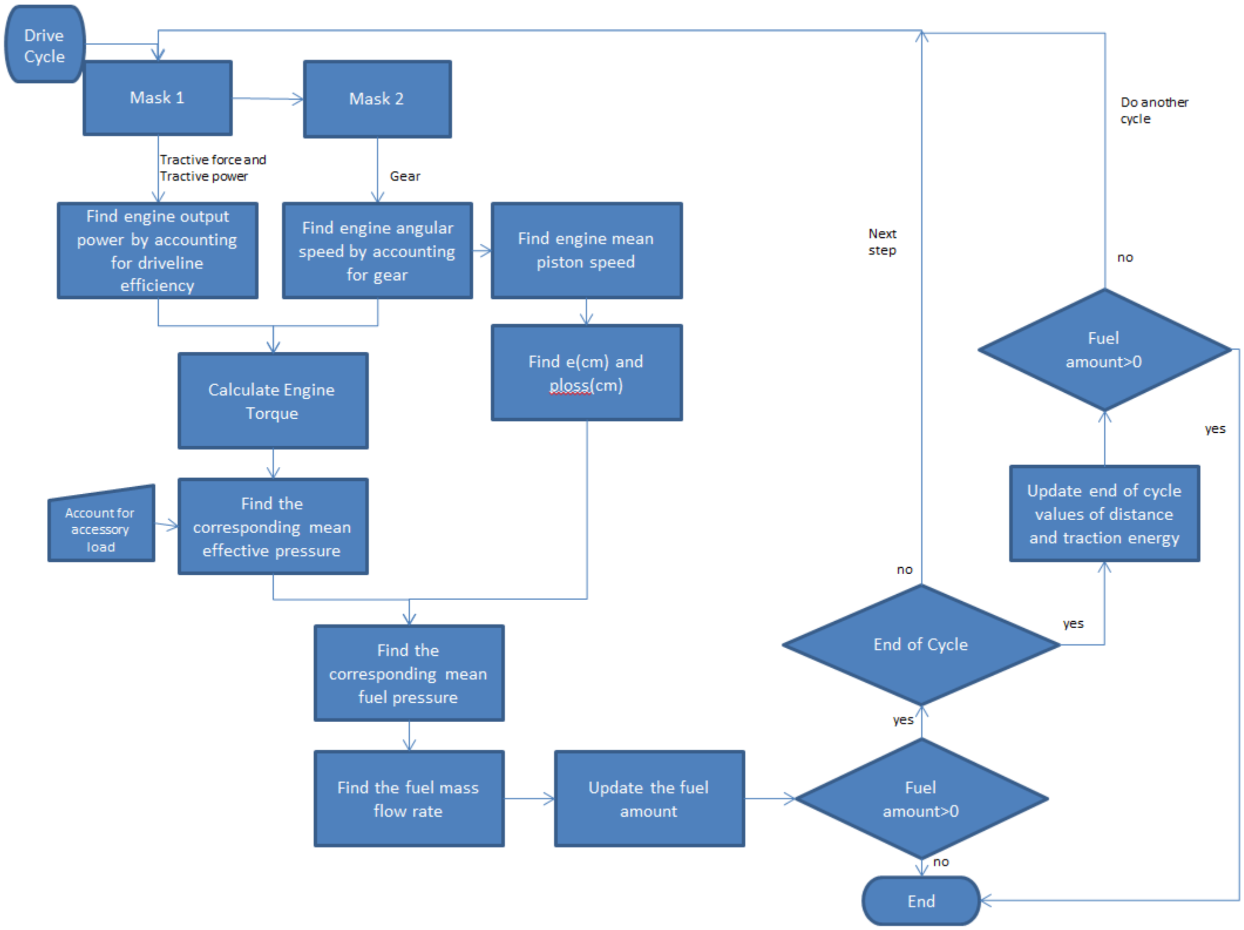

Figure 20. Energy consumption and range estimation

The vehicle performance in terms of energy consumption for the E&EC drive cycles was to be found. The computational processes involved are summed up in Figure 20 and the results in Figure 21.

The net tractive energy figures are a little more than that of propulsion energy figures (Fig. 8) due to the added mass powertrain over the glider mass. The energy consumption comes out to be 696Wh/km which is higher than the vehicle design requirements. And since the acceleration performance is also greater than the requirements, the baseline engine can be downsized to reduce the energy consumption.

Figure 22 shows the actual performance and fuel consumption data of the 2018 Honda HR-V manual. The figures show a discrepancy of about 16% in the fuel consumption data between the approximated and published data. The discrepancy in WTW GHG emissions is of about 57% more although E10 fuel was used. The obvious reasons are simplicity of the model and inaccuracies in the estimated parameters, both relating to the vehicle and drive cycle (EPA uses 5-cycle testing method). The 0-60 acceleration time is under 6% of the published data.

The whole procedure was repeated for a Chevy Malibu 2013 (see Fig 23 to 28) which again shows that the acceleration results are under 6% of the published result, fuel consumption results under 8% and GHG emissions over 50%.

energy_cnsmp	udds505	hwfet	us06city	us06highway	weighted
'Net tractive energy Wh/km'	134.6	98.884	289.06	156.23	161.67
'Fuel energy_Wh/km'	755.28	611.6	928.9	608.1	696.11
'Total energy consumption Wh/km'	755.28	611.6	928.9	608.1	696.11
'Total energy consumption mpgge'	29.586	36.536	24.056	36.746	32.868
'WTW PEU Wh PE/km'	122.64	99.314	150.84	98.744	113.04
'WTW GHG emission g/km'	405.98	328.75	499.3	326.86	374.17
'Range km'	476.13	587.99	387.14	591.38	528.96
'Mass'	1695.5	1695.5	1695.5	1695.5	1695.5

```
City_mpg =

   27.7608


Highway_mpg =

   36.7001


Combined =

   32.8562
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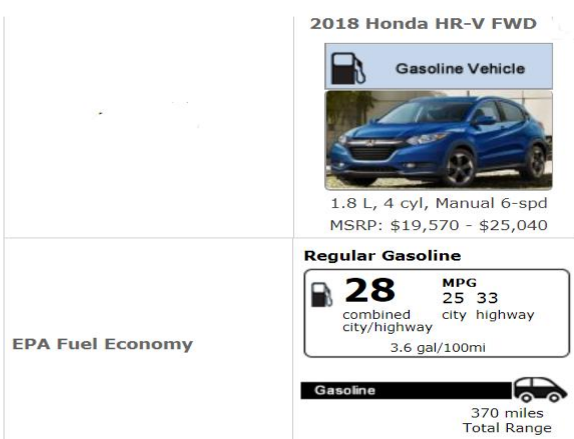
Figure 21. Drive cycle specific Powertrain Energy consumption



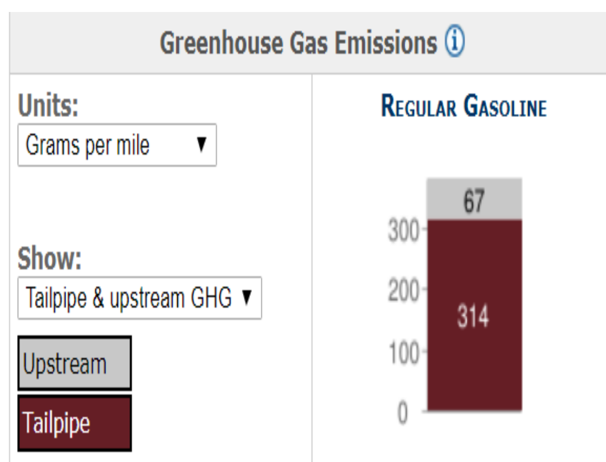


Figure 22. Actual performance and energy consumption data of Honda HR-V [4], [6]

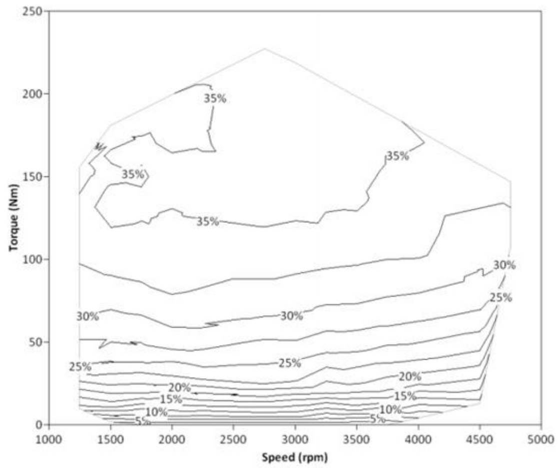


Figure. 23 Chevy Malibu engine map developed in the vehicle using a chassis dynamometer [8]

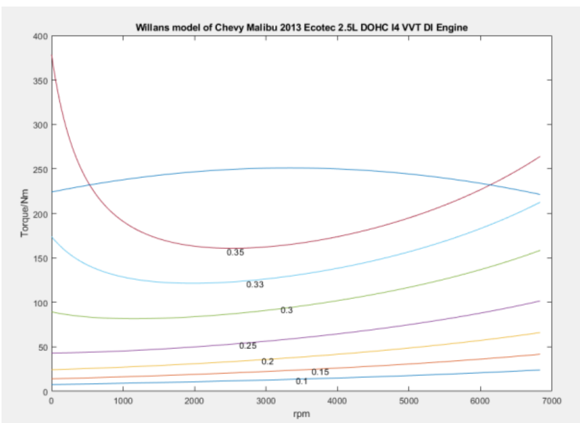


Figure. 25 Willans model

Table 3 Willans model factors

	e	***ploss***
cm^2	-0.00019	0.0049
cm	0.00999	0.0926
1	0.361	1.0409

Parameters	Values
'Test mass kg'	[1.7313e+03]
'Max Speed kph'	[220.4541]
'Acceleration 0-60 mph s'	[8.9700]
'Highway gradeability at 60mph at test mass %'	[30.2420]
'Powertrain sizing:'	' '
'Engine peak power kW'	[147]
'Estimated accessory load kW'	[11]
'Engine mass kg'	[165]
'Transmission mass kg'	[66.3000]
'Transmission gearing'	' '
'1st gear'	[4.5800]
'2nd gear'	[2.9600]
'3rd gear'	[1.9100]
'4th gear'	[1.4500]
'5th gear'	[1]
'6th gear'	[0.7500]
'Reverse'	[2.8400]
'Final drive'	[2.6400]

Figure. 26 Results of powertrain sizing

energy_cnsmp	udds505	hwfet	us06city	us06highway	weighted
'Net tractive energy Wh/km'	138.63	101.51	298.32	159.72	166.02
'Fuel energy_Wh/km'	847.9	796.23	1137.9	860.97	888.18
'Total energy consumption Wh/km'	847.9	796.23	1137.9	860.97	888.18
'Total energy consumption mpgge'	26.354	28.064	19.638	25.954	25.439
'WTW PEU Wh PE/km'	137.69	129.29	184.77	139.81	144.22
'WTW GHG emission g/km'	455.77	427.99	611.63	462.79	477.41
'Range km'	424.12	451.65	316.04	417.68	409.4
'Mass'	1759.5	1759.5	1759.5	1759.5	1759.5

```
City_mpg =

   24.1374


Highway_mpg =

   26.4180


Combined =

   25.4374
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Figure. 27 Energy consumption results

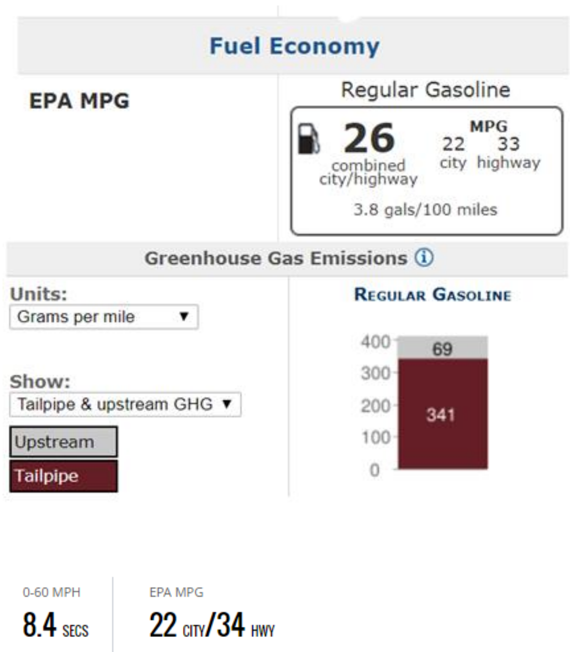

Figure 28 Actual results

The 0-60 acceleration time for the baseline engine considered came to be 9.96 sec (see Fig. 19) which exceeds the requirements. It is known that engine downsizing improves efficiency and thus reduces fuel consumption due to increase in relative load on the downsized engine. The engine i.e. the engine map was obtained from Willans method in which engine size parameters are introduced in the power form of the equation normalizing it to be directly dependent on these size parameter [9]. In this way, fuel consumption and maximum engine torque scale with engine displacement volume V_d and stroke length S.

The mass of the engine is varied as follows: Mass of R18A was known [5]. Since engine mass depends most on engine size and thus engine displacement, following relationship was established:

$$\frac{mass\ of\ R18A}{V_d\ of R18A} = \frac{101}{0.001799} = 56142.3\ kg/m^3$$

$$m_{downsized} = V_{d_{downsized}} * 56142.3\ kg$$
(10)

Power requirement of the downsized engine can be established from the maximum of peak power requirements of the drive cycle (≈85 kW; see Fig. 8), acceleration requirement (≈61 kW; see Fig. 11). A 1.6L engine from the same class was selected for a first iteration (see Fig. 29). The mass of the engine from (10) becomes:

$$m_{R16A} = 0.001595 * 56142.3 = 89.54\ kg$$

The results are shown in Figure 30 and 31 respectively. On the performance side, the 0-60 acceleration time has increased and top speed has decreased. On the energy consumption side, the simulation results show that mileage has increased from about 32 mpg to 36 mpg.

```
%Engine specs Honda R16A
%Vd=1595 cc
%HP=93 kW @ 6500 rpm
%T=151 Nm @4300 rpm
%Redline=6800 rpm
%Bore=81mm
%Stroke=77.4mm
```

Figure 29 Engine specifications

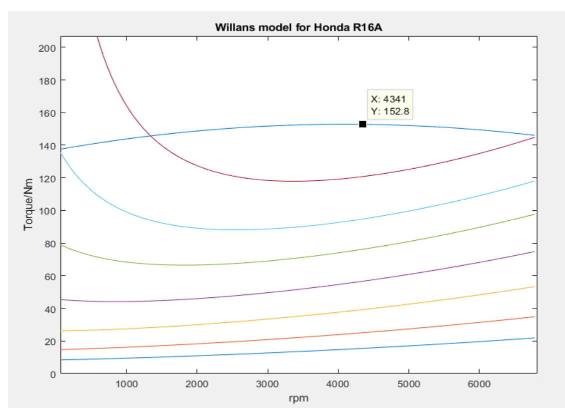

Figure 30 Scaled Willans model of the downsized engine

Parameters	Values
'Test mass kg'	[1.6558e+03]
'Max Speed kph'	[191.8042]
'Acceleration 0-60 mph s'	[11.1300]
'Highway gradeability at 60mph at test mass %'	[18.6144]
'Powertrain sizing:'	' '
'Engine peak power kW'	[93]
'Estimated accessory load kW'	[8]
'Engine mass kg'	[89.5000]
'Transmission mass kg'	[66.3000]
'Transmission gearing'	' '
'1st gear'	[3.6420]
'2nd gear'	[1.8850]
'3rd gear'	[1.3610]
'4th gear'	[1.0240]
'5th gear'	[0.8300]
'6th gear'	[0.6860]
'Reverse'	[3.6730]
'Final drive'	[4.7050]

Figure 31 Performance results of the downsized engine R16A

energy_cnsmp	udds505	hwfet	us06city	us06highway	weighted
'Net tractive energy Wh/km'	134.38	99.611	288.02	157.73	162.23
'Fuel energy_Wh/km'	661.42	528.04	867.01	567.4	631.89
'Total energy consumption Wh/km'	661.42	528.04	867.01	567.4	631.89
'Total energy consumption mpgge'	33.784	42.317	25.773	39.382	36.205
'WTW PEU Wh PE/km'	107.4	85.745	140.79	92.137	102.61
'WTW GHG emission g/km'	355.53	283.83	466.04	304.99	339.65
'Range km'	543.7	681.03	414.77	633.79	582.67
'Mass'	1684	1684	1684	1684	1684

```
City_mpg =

   31.1404


Highway_mpg =

   40.0276


Combined =

   36.2061
```

Figure 32 Energy consumption results

Further downsizing by substituting the stroke length and displacement values of a L13A engine (see Fig. 33 to 36).

L13A i-VTEC

- Available in the Honda Fit (Japan series GE6 / GE7), Honda Airwave in Japan and the European Honda Civic.
  - SOHC 16 valve i-VTEC
  - Displacement: 1,339 cc (81.7 cu in)
  - Bore x Stroke: 73.0 mm x 80.0 mm (2.87 x 3.15 in)
  - Compression Ratio: 10.5:1
  - Horsepower: 73 kW (99 PS; 98 hp) (99 PS; 98 hp) / 6,000 rpm
  - Torque: 127 N·m (94 lb·ft) / 4,800 rpm

Figure 33 Engine specifications [10]

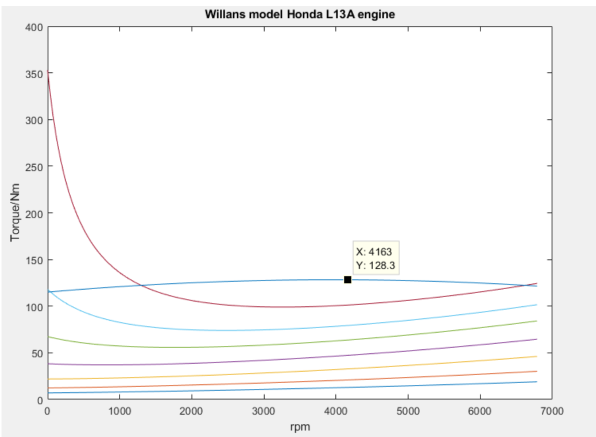

Figure 34 Scaled Willans model for L13A

Parameters	Values
'Test mass kg'	[1.6414e+03]
'Max Speed kph'	[185.1656]
'Acceleration 0-60 mph s'	[13.6500]
'Highway gradeability at 60mph at test mass %'	[14.1276]
'Powertrain sizing:'	' '
'Engine peak power kW'	[73]
'Estimated accessory load kW'	[8]
'Engine mass kg'	[75.1000]
'Transmission mass kg'	[66.3000]
'Transmission gearing'	' '
'1st gear'	[3.6420]
'2nd gear'	[1.8850]
'3rd gear'	[1.3610]
'4th gear'	[1.0240]
'5th gear'	[0.8300]
'6th gear'	[0.6860]
'Reverse'	[3.6730]
'Final drive'	[4.7050]

Figure 35 Performance results for L13A which shows that acceleration requirements are not met. Also peak power requirements are not met and in reality, the drive schedule will not be followed

energy_cnsmp	udds505	hwfet	us06city	us06highway	weighted
'Net tractive energy Wh/km'	133.4	98.91	286.35	155.24	160.5
'Fuel energy_Wh/km'	603.38	480.13	817.88	527.68	584.55
'Total energy consumption Wh/km'	603.38	480.13	817.88	527.68	584.55
'Total energy consumption mpgge'	37.034	46.541	27.321	42.347	39.206
'WTW PEU Wh PE/km'	97.978	77.964	132.81	85.686	94.921
'WTW GHG emission g/km'	324.33	258.08	439.63	283.64	314.21
'Range km'	596	749	439.69	681.5	630.95
'Mass'	1669.6	1669.6	1669.6	1669.6	1669.6

```
City_mpg =

   33.8287


Highway_mpg =

   43.2693


Combined =

   39.2098
```

Figure 36 Energy consumption results illustrative of decreasing fuel consumption due to increasing relative load on smaller engines

The reason for the increase in mileage can be quantified as follows: As stated previously, downsizing an engine increases the relative load on the engine and hence increases the efficiency (see Table 4). Note that US06 highway has the highest mean efficiency which can be attributed to the highest average power demand of the cycle (see Fig. 8).

Table 4. Mean efficiency result of the baseline and downsized engine for the E&EC drive cycles

	R18A	R16A	L13A
UDDS 505	7.5%	8.32%	8.97%
HWFET	9.33%	10.69%	11.66%
US06 city	11.74%	12.45%	13.08%
US06 highway	13.88%	14.87%	15.87%

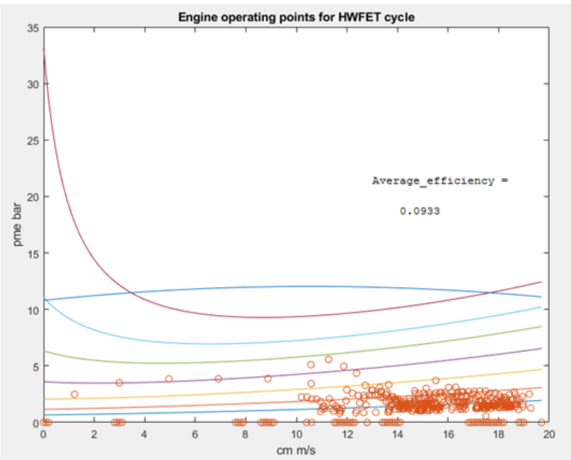

Figure 37 Lower average power requirement for HWFET cycle results in lower engine efficiency operation of engine

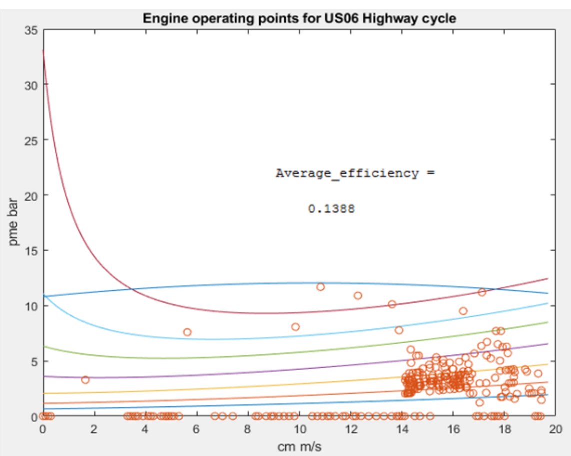

Figure 38 Higher average power requirement for US06 highway cycle results in relatively high operation efficiency for engine

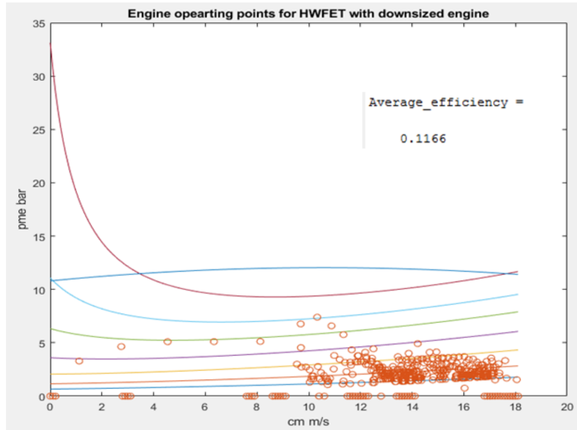

Figure 39 Illustrative of the fact that engine downsizing increases the relative load on engine and hence operates at higher efficiency

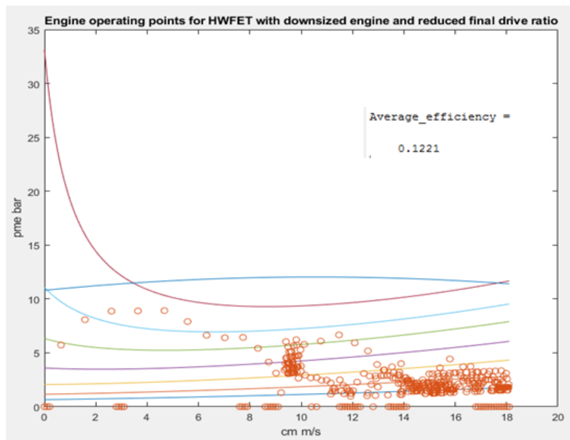

Figure 40 Besides engine downsizing, transmission can be tweaked to increase relative load on engine but this will affect performance requirements

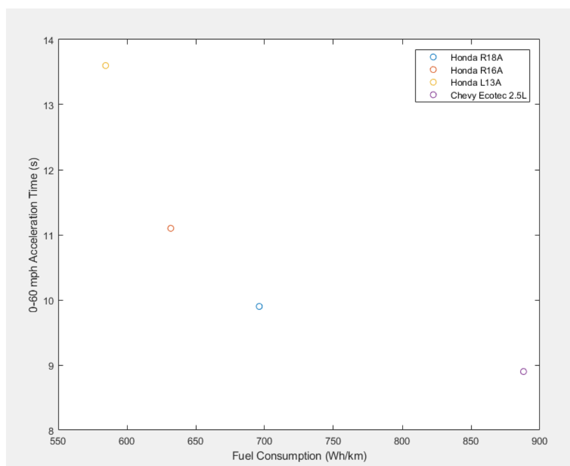

Figure 41 Fuel consumption vs Acceleration time for varying engine sizes

The fuel consumptions for all the engines simulated is way high than the target which is 370 Wh/km. The lowest is for L13A engine but the engine does not satisfy the peak power requirements of cycles and in reality, the drive schedule won't be followed since engine output would be limited. Also it does not fulfill the acceleration requirement. The R16A engine is satisfactory for the acceleration requirement and the peak power requirements of all the weighted 4 cycle. Its energy consumption is about 630 Wh/km WTW GHG emissions of about 340 g/km which are higher than the requirements. And since, as discussed a smaller engine than that does not satisfy the acceleration requirement and peak power requirement.

For conventional vehicles, the only option that remains practically to reduce the fuel consumption is to use smaller engines with increase in air and fuel content for combustion to meet the performance requirements and lower fuel consumptions, that is, air boosting (supercharged/turbocharged engines).

Apart from engine technologies (like direct injection and VVT), other domains that impact positively towards lowering fuel consumptions are optimizing transmission gear ratios and electrification of accessory loads (operate only when needed if they are electrically powered, but they impose a parasitic demand all the time if they are engine driven) [11]. Note that a change in gear ratios to affect a higher load on engine will result in a decrease in performance (see Fig. 40).

Part III

Battery Model

Li-ion batteries have non-linear charge/discharge characteristics specific to the battery chemistry. Cells are cycled to get the characteristics experimentally. Experimental data for charge/discharge internal cell resistance and voltage wad available for a 'A123' cell (3.3V, 19Ah) as a function of state of charge. The data was curve fitted and linearly scaled to a pack level to be used as a battery model.

Low specific energy of current battery technology is a big issue and as such, battery packs in xEVs bear a substantial fraction of the net mass of the vehicle. Apart from the cell mass, at pack level, various other components like structural plates, cooling system, packaging components, wiring harness, ECM, all add to the pack. Hence, for the EV model, battery pack mass was accounted (see App. 1)

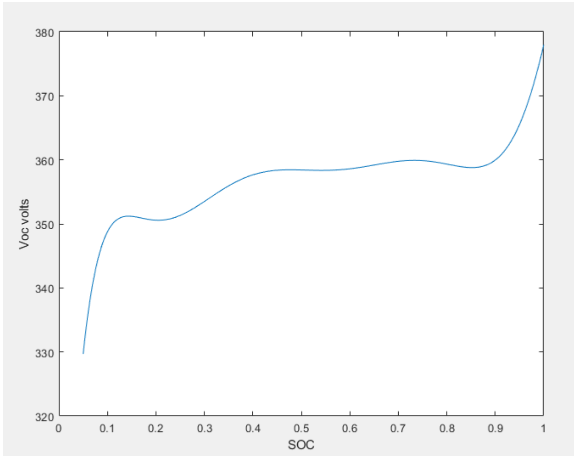

Fig. 42 Curve fitted voltage characteristics for 'A123' cell

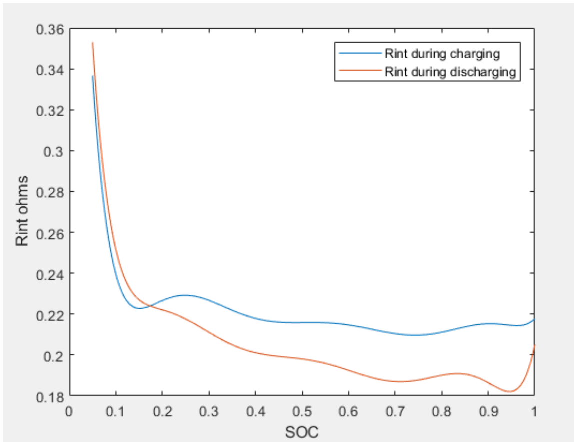

Figure 43 Curve fitted internal resistance characteristics

Willans motor model

The Willans method is applicable to e-machine as well. The 'e' values obtained are typical of electric machines. The 'ploss' values are also almost negligible, which is expected of electric machines.

Table 4. Willans parameters for Bosch motor

	e	***ploss***
cm^4	2.675e-9	-2.8643e-6
cm^3	-4.7293e-7	-3.6401e-4
cm^2	1.671e-6	0.1051
cm	0.0036	-2.124
1	0.749	13.542

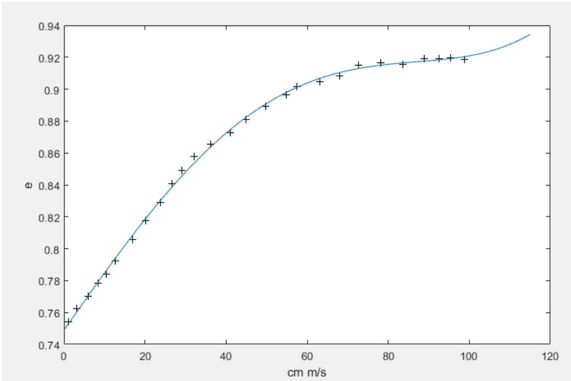

Figure 44 Modelled thermodynamic efficiency of conversion ‘e’ shows the typical high values for electric motors

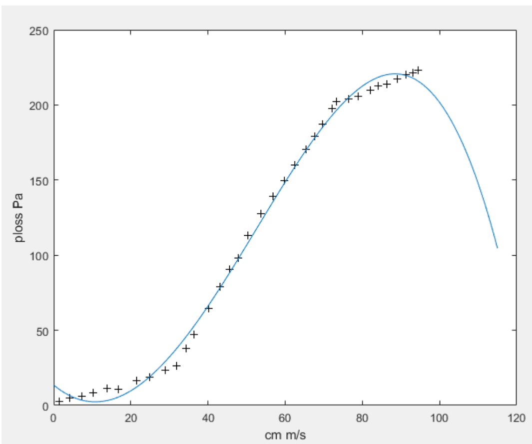

Figure 45 Low losses typical of electric machines

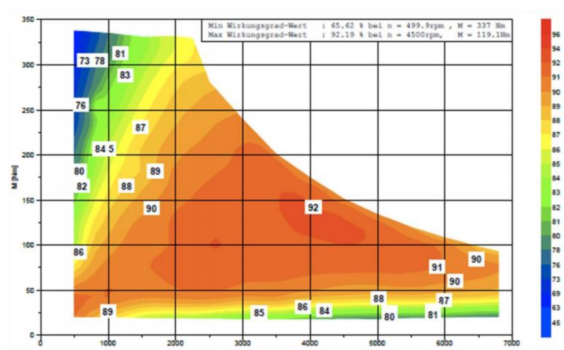

Fig. 46 Bosch IMG efficiency map

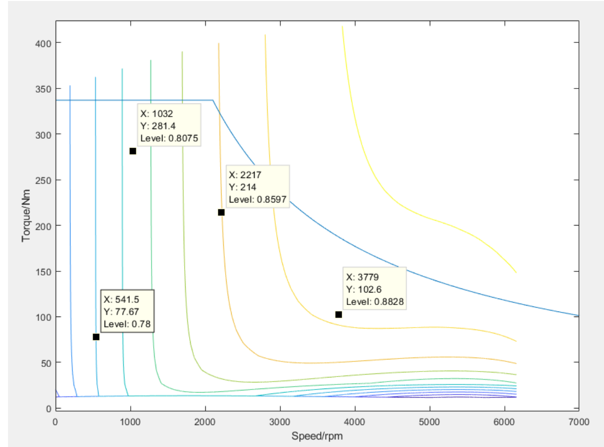

Figure 47 Efficiency map of the Bosch IMG from Willans model shows good agreement with the original map

The performance results were found on basis of WOT test results with max torque curve of motor (see Fig. 48)

Parameters	Values
'Test mass kg'	[1.9944e+03]
'Max Speed kph'	[183.3113]
'Acceleration 0-60 mph s'	[12.9300]
'Highway gradeability at 60mph at test mass %'	[11.5730]
'Powertrain sizing:'	' '
'Motor peak power kW'	[73]
'Estimated accessory load kW'	[1.2000]
'Single reduction gear'	[9]
'Battery energy capacity kWh'	[46.0845]
'Battery peak power kW'	[73000]
'Battery mass'	[494.4427]

Figure 48 Performance results for the BEV with Bosch IMG and ‘A123’ battery pack

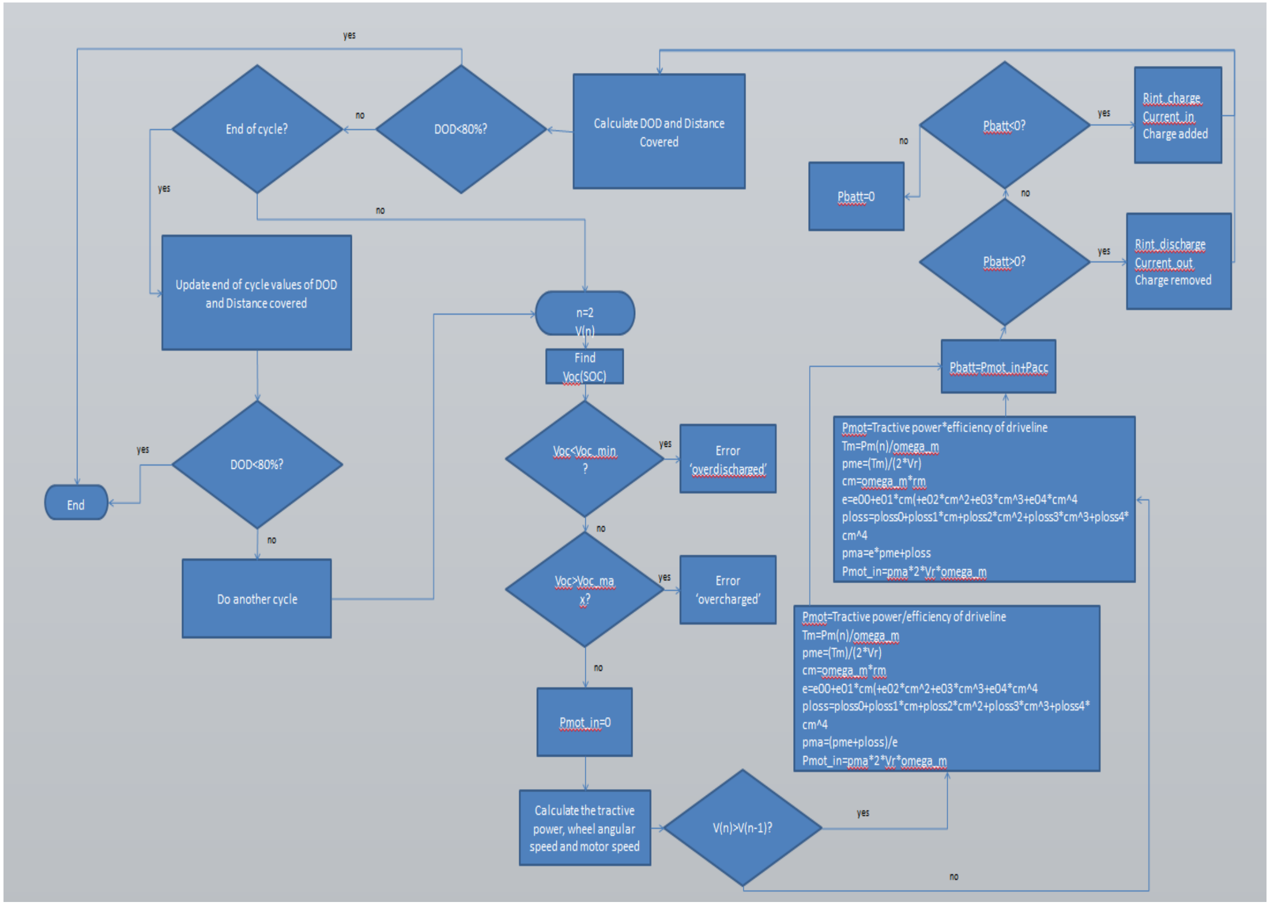

Figure 49 Flowchart depicting computational process for estimating the energy consumptions and range

energy_cnsmp	udds505	hwfet	us06city	us06highway	weighted
'Net tractive energy Wh/km'	101.48	112.79	150.83	161.86	136.92
'Battery energy_Wh/km'	168.96	154	293.91	210.22	203.23
'Total energy consumption Wh/km'	168.96	154	293.91	210.22	203.23
'Total energy consumption mpgge'	123.42	135.41	70.95	99.197	106.61
'WTW PEU Wh PE/km'	8.9734	8.1785	15.609	11.164	10.793
'WTW GHG emission g/km'	132.97	121.19	231.3	165.44	159.93
'Range km'	204.56	224.44	117.6	164.41	176.71
'Mass'	1994.4	1994.4	1994.4	1994.4	1994.4

```
City_mpgge =

  106.1038


Highway_mpgge =

  107.1647


Combined =

  106.7085
```

Figure 50 Energy consumption results for the BEV

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Nomenclature

$\boldsymbol{F_{tr}}$	Tractive force
$\boldsymbol{F_{roll}}$	Rolling resistance
$\boldsymbol{F_{aero}}$	Aerodynamic drag
$\boldsymbol{F_{hill}}$	Hill climbing force
$\boldsymbol{F_{acc}}$	Inertial resistance
p_{me}	Mechanical mean effective pressure
e	Thermodynamic conversion efficiency
p_{ma}	Fuel mean effective pressure
p_{mloss}	Mean effective pressure loss
m_a	Fuel mass in cylinder
η	Engine efficiency
ω_e	Engine angular speed
λ	Air/fuel ratio
ζ	Injection/ignition timing
x_{egr}	Exhaust gas rate

Appendix

I. Calculation of battery pack mass

Packaging mass per 15s3p cells = 5.4 kg

Cell mass = 0.496 kg

For a pack with 7x15sx7p configuration (a 46kWh pack),

Module added mass for series cells per module = No of cells in series per module/15 = 105/15 = 7 kg

Module added mass for parallel cells per module = No of cells in parallel per module/3 = 7/3 = 2.34 kg

*Total module added mass = 5.4*7*2.34 = 88.2 kg*

*Total mass of all cells = 7*15*7*cell mass = 364.5 kg*

Total pack mass = 88.2 + 364.5 = 452.76 kg

Accounting for 10% added mass for packaging

*Total mass = 452.76*1.1 = 498 kg*