Eco-marathon Car Driving Pattern and Miles Per Gallon

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Abstract

Annually, young students participate in the Shell Eco-marathon, a competition organised by Shell, in which teams are to present their design of cars that can drive extreme distances on 1 gallon of fuel. The first category in the competition is for the teams to design very aerodynamic cars and the second category is to design cars similar in body structure to the regular passenger car. Based on the allowed driving pattern and innovation of the teams in design of the vehicles and the engines, over 4,800 km/litre is the 2011 record compared with about 60 km/litre in the modern efficient regular cars. In this paper, we model the driving pattern around the Honda GX series engines for team using the internal combustion engine, a possible performance of 1,360 km/litre could be reached in the mixed mode driving using an engine whose brake specific fuel consumption is 23% lower and that can provide 33% more torque than the regular GX series.

Keywords: *Shell Eco-marathon, fuel economy, driving pattern, mpg.*

1. Introduction

Since 1939, Shell researchers began experimenting on vehicles that could make more mileage per gallon (mpg) of fuel and now annually, since, 1985 young engineers and scientist have been challenged to develop cars that can make extreme mileage on a gallon (Shell 2012). The efficient regular kinds of vehicles, as a comparison, have typical mileage of about 50 mpg which is about 21 km/litre. Earlewine *et al*. (2010) surveyed 783 vehicles in real time using Global Positioning System (GPS) tracking technique and found the economy to be in the range 12.5-66.7 km/litre. The experimental vehicles keep advancing and the global current record (2011) is 4,896.1 km/litre achieved by France's Polytech' Nantes (Shell 2012). The participating teams can enter into either of Prototype category or the Urban Concept category.

The prototype category rule states that the maximum vehicle weight without the driver is 140 kg and be designed fuel efficient and aerodynamically with maximum frontal cross-section of 130×100 cm and maximum length 350 cm. Most of the vehicles in this category are usually with 3 wheels and sometimes with 2 wheels, a decision of which is up to the participating teams like in Fig. 1.

The urban concept category mandates that the frontal height be 100-130 cm and a width of 120-130 cm with a total length of 220-350 cm and maximum weight excluding the driver to be 205 kg and would appear like the regular passenger cars in Fig. 2.

Fig. 1. Shell eco-marathon - prototype car.

Fig. 2. Shell eco-marathon - concept car.

The design of the vehicle and the driving patterns account for the extreme mileage achievable by the teams. The drivers are allowed to accelerate the vehicle and then switch off the engine during coasting and repeatedly in this cycle.

Unlike the Formula car race competition, the winning the competition is only dependent on how much fuel is consumed to complete the race circuit given and not how fast you speed or who completes the track first, but the vehicles must make a minimum of 24.14 km/hr (15 mph) and a maximum of 30 mph. The engine type can be internal combustion engine (ICE) or electrically powered. The ICE can run on a wide range of fuels like ethanol or petrol. The engine can also be electrically powered with hydrogen, solar or a battery source. The new rule for 2012, unlike in the previous edition of the competitions, now allows for use of hybrid powered vehicles.

Fuel economy is described by Song *et al*. (2010) as the ratio of the driving distance to the fuel consumption in a whole cycle. The performance of a car engine can be described (Adeniyi 2008; Turrentine and Kurani 2007) in terms of good fuel economy, low emissions, high-power to weight ratio, onboard energy and good driveability.

Oil companies, Motor manufacturers, customers, government authorities and researchers are the parties keen to getting better fuel economy. While the oil companies have interest in fuel economy for better planning in the formation of better oil/fuel, motor manufacturers need to know available options and limitations posed by fuel and lubricants and the effect of transmission, tyres, vehicle drag, and weight among other parameters. Government authorities and agencies set emission level, they depend on research to formulate this rules. Customers are more interested in how much savings can be made while researchers are interested in developing the state of the art.

The motive of this paper is to analyse driving patterns as they affect fuel consumption. Small Honda engines in the GX model range are used by many of the teams. Students also design similar engines as in the work of Ali *et al*. (2011), thus justifying their use in this simulation.

2. Modelling Driving

Driving is simulated based on the allowed driving cycle. It is assumed that the engines have fully warmed up. The effect of fuel consumption during cold-startup (Blackmore and Thomas 1977) does not count during the completion as the teams must have warmed the engine before entering the track. An interface was developed to run the simulation for a range of Honda engines as shown in Fig. 3. It is also assumed that the teams could develop better engines for this competition, so the application is developed to at 100% Honda engine or at a hypothetical increased performance. The increased performance is measured by a torque increase and lower Brake Specific Fuel Consumption (BSFC). The test case for the improved version otherwise called extended engine was taken to 33% more torque and 67% of BSFC. The Honda engine trademark models GX25, GX35, GXH50, GXV50, GXV57, GX100, GX120, GX160 and GX200 were simulated and by the extension, the models are preceded with letter '*E*'. Model GX25 extended is for example marked EGX25 and so on.

The race circuit is assumed to have a maximum inclination of from 0 to 0.05^o similar to the Rockingham Oval circuit (Rockingham 2008). The simulation was done both for a level road and for the maximum road inclination, as more fuel is consumed when climbing a hill.

In the code, the following terms are defined.

2.1 Fuel Consumption

Fuel quantity (Q_f) in m^3 can be computed using:

$$Q_f = (BSFC \times t \times P) / \rho, \qquad (1)$$

where: $BSFC$ = Brake Specific Fuel Consumption (kg/kWhr); t = time in hours; P = power in kW; and ρ = density in kg/m^3.

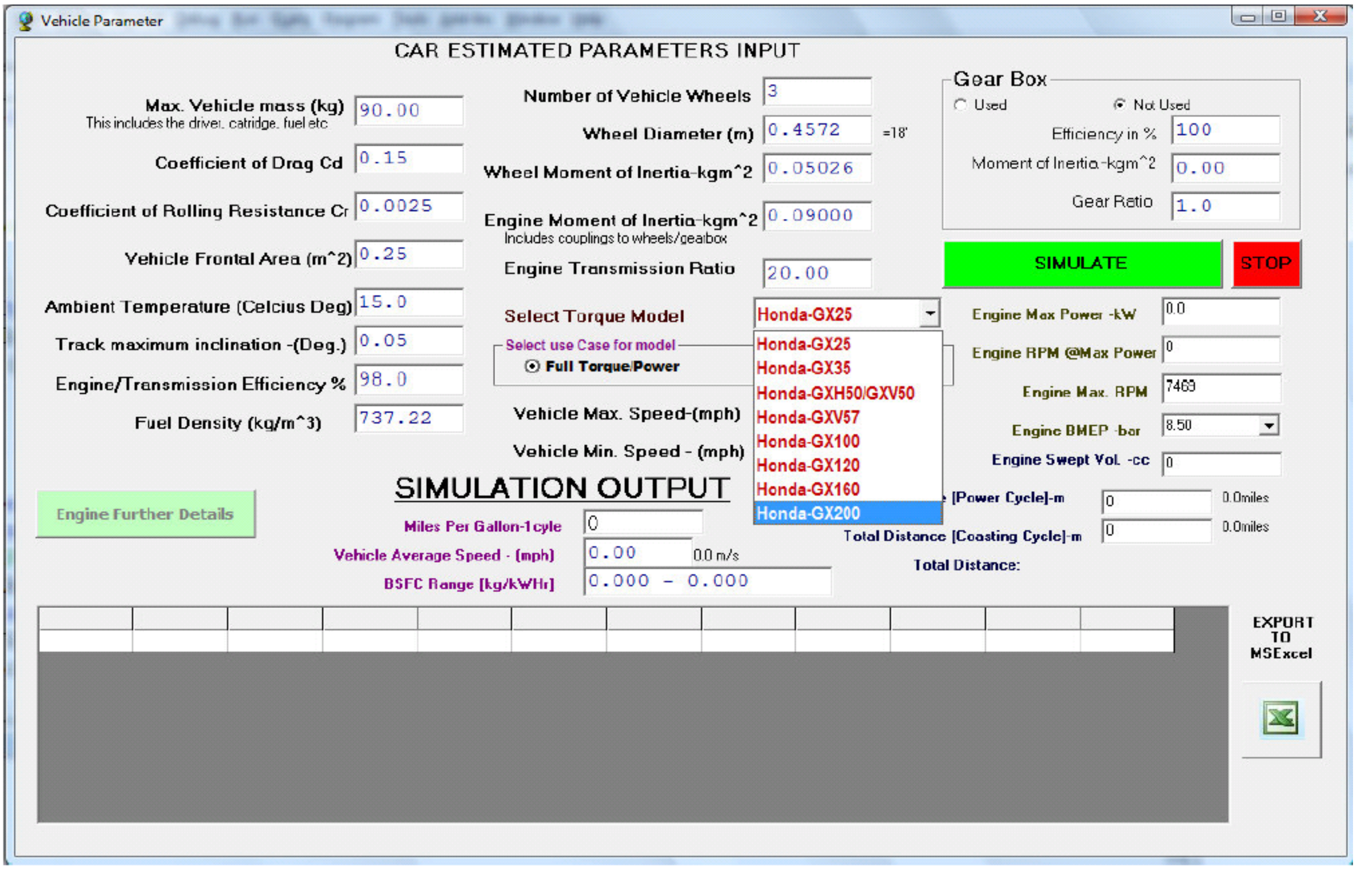

Fig. 3. Application interface developed.

Brake Specific Fuel Consumption (*BSFC*) is defined as:

$$BSFC = (Q_c \times \rho) / (1{,}000 \times P_e) = \dot{m}_f / BP, \quad (2)$$

where: Q_c is the fuel consumption per hour; P_e is the engine power in kW; $\dot{m}_f$ = fuel mass flow rate (kg/hr); and BP = brake power (kW).

Indicated Specific Fuel Consumption (*ISFC*) is defined as:

$$ISFC = \dot{m}_f / P_i, \quad (3)$$

where P_i is the indicated power (kW).

The data specified in the Honda (Adeniyi 2008) data sheet have been extended given that only the *BSFC* at the maximum power is specified. It is assumed that the *BSFC* is 100% at the maximum power and 95% at the boundaries giving rise to the implied *BSFC* over the engine revolution in Fig. 4.

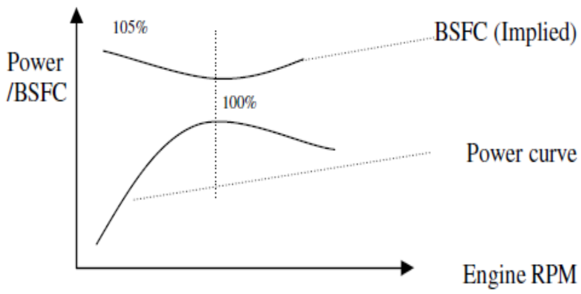

Fig. 3. Implied power/BSFC vs RPM.

2.2 Vehicle Total Distance

The kinematic equation of motion is used to calculate the distance (*S*) covered, but integrated over the whole circuit summing at short time intervals, $t = \Delta t$. For high accuracies:

$$S = ut + at^2/2. \quad (4)$$

where: $t = \lim_{\Delta t \to 0} \Delta t$; a = acceleration (m/s^2 given later); and u = vehicle speed at the last computation.

2.3 Vehicle Average Speed

The Taylor method is used to compute the average using the nodal values computed over the driving cycle from the iterative solution of:

$$u_{i+1} = u_i + at, \quad (5)$$

where: u_{i+1} is the current velocity at time t; and u_i is the vehicle velocity at the initial time step.

2.4 Engine Propulsion

To provide driving power to the wheels and move the vehicle, the engine is required to provide power sufficient to overcome the following:

- Overall vehicle weight;
- Transmission resistance; and
- Road load.

The road resistance, R (N), is modelled as:

$$R = 9.81\, m\, C_r + C_d\, \rho_a\, A\, V^2 / 2 + 9.81\, m \sin(\theta), \quad (6)$$

where: C_r = Coefficient of rolling resistance; C_d = Coefficient of drag; A = frontal vehicle area (m^2); V = Velocity of the vehicle; θ = Track inclination (degree/radian); m = total mass of the vehicle (kg); and ρ_a = ambient air temperature (kg/m^3).

The propulsive force, F (N), available at the wheels of the vehicle is given by:

$$F = [T / (0.5\, D_w)] \times G_r, \quad (7)$$

where: T = Instantaneous Torque (Nm), G_r = Transmission ratio (Gear ratio × Final drive ratio) ratio; and D_w is wheel diameter (m).

The acceleration, a (m/s^2), is given by:

$$a = \frac{\left(\delta_i \dfrac{TG_r}{0.5 D_w}\eta_e - R_V\right)}{\overline{M}}, \quad (8)$$

where: δ_i = Kronecker delta; i = 1 for driving, and i = 0 for coasting mode, η_e is engine efficiency; R_V is road resistance at velocity V, and $\overline{M}$ = equivalent mass (kg) of the system:

$$\overline{M} = m + \frac{4}{D_w^2}\left\{\frac{I_e G_e^2}{\eta_e} + \frac{I_g G_g^2}{\eta_g} + I_w\right\}, \quad (9)$$

where: I_g = Moment of inertia of the gear (kg·m^2); I_e = moment of inertia of the engine (kg·m^2); I_w = moment of inertia of the wheel; G_e = engine transmission ratio; η_e = engine efficiency; and η_g = gear efficiency.

2.5 Engines Specifications

Table 1 shows the specifications of the selected engines extracted from Honda (Honda 2008) and without any extensions. The models numbers carry the engine capacity. The GX25 has a capacity of 25cc while GX200 has a 196cc engine capacity.

Table 1. Engines specifications.

Model	*P* (*kW*)	Q_c (l/hr)	*BSFC* @ P_{max} (*kg*/*k*Whr)	Mass (kg)
GX25	0.72	0.58	0.5529	2.88
GX35	1.00	0.71	0.5234	3.33
GXH50	1.88	0.91	0.4193	5.50
GXV57	1.50	0.58	0.2851	5.40
GX100	2.10	0.77	0.4193	10.6
GX120	2.60	1.00	0.2835	13.0
GX160	3.60	1.40	0.2867	15.0
GX200	4.10	1.70	0.3057	16.0

2.6 Simulation Data

The simulation was carried out using the data in Table 2.

Table 2. Simulation entry data.

Description	Value	Description	Value
Mass (kg)	90	Track maximum inclination	0.05°
C_d	0.15	Fuel Density (Gasoline) (kg/m^3)	737.22
C_r	0.0025	Vehicle number of wheel	3
Vehicle Frontal Area (m^2)	0.25	Wheel moment of inertia (kg·m^2)	0.05
Ambient Temperature (^{o}C)	15.0	Engine Moment of inertia (kg·m^2)	0.09

Table 3. Engine performance data.

	Speed		MPG		Ave. Speed		Max. Power		*BSFC - LR*		*BSFC - Inc*	
	mph				mph		kW		kg/kWhr		kg/kWhr	
Model	Min.	Max.	0.0^o	0.05^o	0.0^o	0.05^o	0.0^o	0.05^o	Min.	Max.	Min.	Max.
Original Version of Honda Engines												
GX35	*17.0*	*30.0*	757.48	668.37	*23.04*	*23.17*	1.128	1.134	*0.518*	*0.547*	0.518	0.547
GX50	*13.0*	*30.0*	1175.82	1014.4	*20.53*	*20.64*	1.573	1.572	*0.421*	*0.433*	0.421	0.433
GX57	*21.0*	*26.0*	2220.65	1930.74	*23.47*	*23.46*	1.353	1.351	*0.294*	*0.298*	0.291	0.298
Extended Versions for this paper												
EGX35	*17.0*	*30.0*	1084.7	950.37	*23.02*	*23.18*	1.456	1.455	*0.346*	*0.365*	0.345	0.365
EGX50	*13.0*	*30.0*	1712.86	1473.85	*20.53*	*20.64*	2.091	2.09	*0.281*	*0.288*	0.281	0.288
EGX57	*21.0*	*26.0*	3177.01	2766.15	*23.56*	*23.55*	1.815	1.812	*0.194*	*0.199*	0.194	0.199

NB: *LR* = Level Road, *Inc* = Inclined road.

3. Results

Table 3 shows the simulated performance of selected GX range engines and the corresponding extensions version based on this paper. Velocity is specified in mph in this paper because the competition regulation specifies same as mph. 1 mph = 0.447 m/s = 1.609 km/hr.

Possible driving pattern whilst maintaining the 15-30 mph regulations are show in Figs. 5 and 6. Specific results are also shown for the GX57 engine in Figs. 7-11.

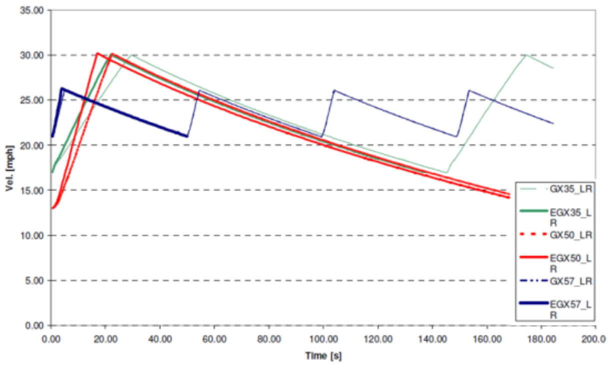

Fig. 6. Velocity-time graph - Level road (EGX = Extended version of GX engines).

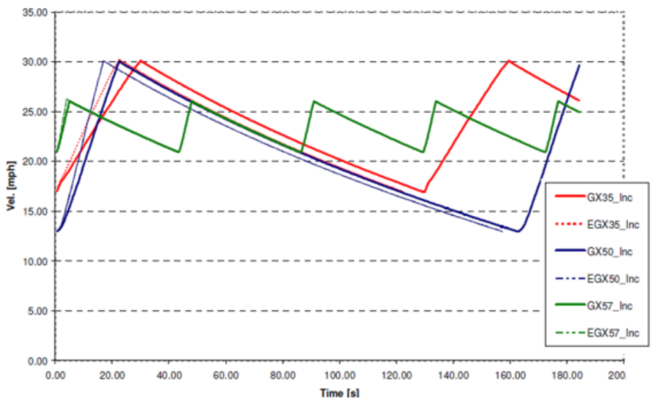

Fig. 5. Velocity-time graph - 0.05^o inclined road.

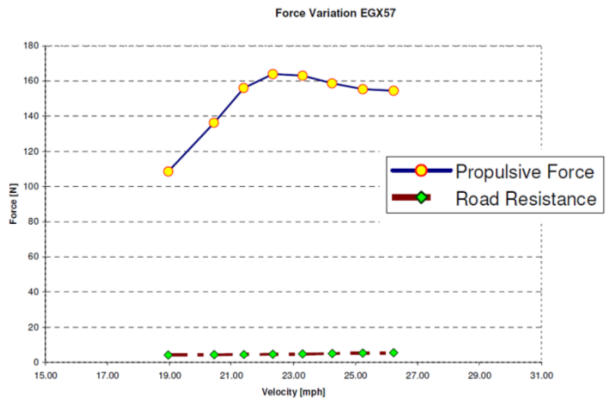

Fig. 7. Driving force and road resistance in the cycle.

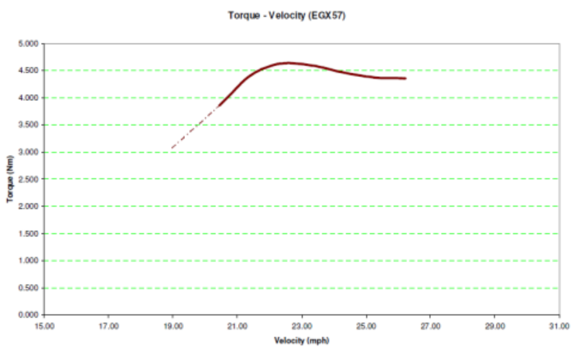

Fig. 8. Driving torque vs velocity (EGX57).

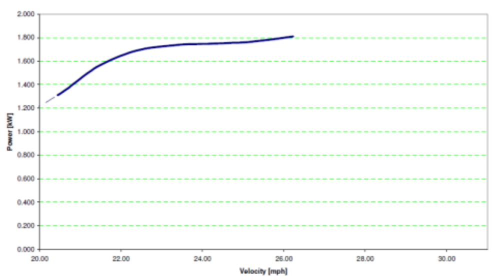

Fig. 9. Engine power - velocity (EGX57).

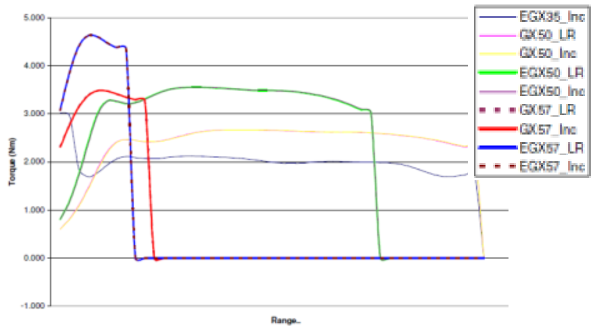

Fig. 10. Torque pattern over same range.

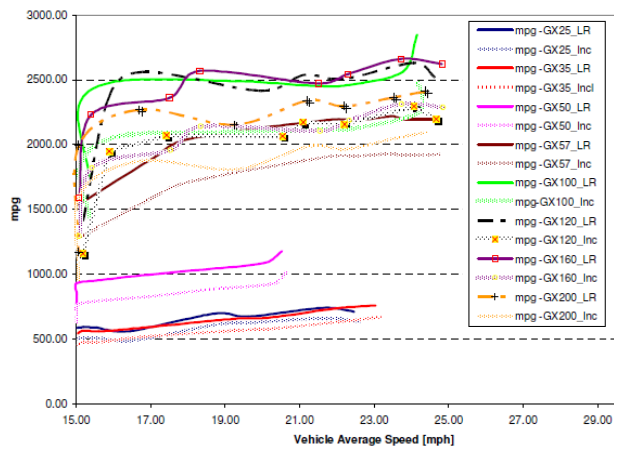

Fig. 11. MPG vs. average speed.

4. Conclusion

Driving pattern and engine designs are the key to getting better fuel economy. Fuel can be saved by switching off the engines rather than idling when a vehicle stops for long periods. This applies to regular car driving. In this work, several engine models were simulated, the best fuel consumption is achieved with the GX57 model which reaches over 2,200 mpg (935.3 km/litre) and by extending this engine for the competition up to 3,200 mpg (1,360 km/litre) is achievable with a 67% better brake specific fuel consumption and 33% more torque. The use of hybrid power technology such that the vehicle could switch from internal combustion engine to an alternative source of power will make the teams achieve better mpg in the Shell Eco-marathon competition.

5. Acknowledgments

Prof. Nicos Ladommatos of University College London (UCL), London, England UK, supervised the MSc thesis, his contributions and undergraduate teaching notes were highly valuable during the research work.

The Department of Mechanical Engineering, UCL, sponsored A.A. Adeniyi to Corby for the 2008 Shell Eco-Marathon in Northampton.

Petroleum Technology Development Fund (PTDF) provided the research fund on behalf of the Federal Government of Nigeria.

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