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Comparative analysis of the energy consumption and CO_2 emissions of 40 electric, plug-in hybrid electric, hybrid electric and internal combustion engine vehicles

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ABSTRACT

This paper analyses the results of the Royal Automobile Clubhallo's 2011 RAC Future Car Challenge, an annual motoring challenge in which participants seek to consume the least energy possible while driving a 92 km route from Brighton to London in the UK. The results reveal that the vehicle's power train type has the largest impact on energy consumption and emissions. The traction ratio, defined as the fraction of time spent on the accelerator in relation to the driving time, and the amount of regenerative braking have a significant effect on the individual energy consumption of vehicles. In contrast, the average speed does not have a great effect on a vehicles' energy consumption in the range 25–70 km/h.

1. Introduction

After the launch of the Future Car Challenge (FCC) by the Royal Automobile Club (RAC) in 2010, the event was again held in November 2011. Growing economic, environmental and health-related concerns about the impacts of road transport have put regulatory pressure on the automotive industry to develop more fuel-efficient vehicles. The aim of the FCC is to drive a 91.94 km route from Brighton to London in England using as little energy as possible.

All road-legal electric, plug-in hybrid, hybrid and up to 110 gCO_2/km (New European Driving Cycle) internal combustion engine passenger motor cars and light commercial vehicles produced after January 1st 2001 were eligible for this competition (Royal Automobile Club, 2011). A minimum time of 2 h and 45 min and a maximum time of three and a half hours were set including a 15–30 min stop-over at approximately half way. Two adult passengers had to be in participating vehicles that were classed by power train type, vehicle size and by type of build (Table 1).

This paper analyses the correlation between various parameters and individual vehicles' energy consumption. The environmental impact of the participating vehicles – i.e. the well-to-wheel and tank-to-wheel CO_2 emissions – is studied as well as individual driving behaviour.

1.1. Methodology

The 2011 RAC FCC featured 26 pure electric, four plug-in hybrid electric, four hybrid electric and six internal combustion engine vehicles. To compare the energy consumption of vehicles with varying power train types, the 'tank-to-wheel' energy

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Table 1
Vehicle entry classes.

Power source	Vehicle size	Build
Electric Vehicle (EV)	Small (A&B)	Prototype
Plug-in Hybrid Electric Vehicle (PHEV)	Regular (C)	Production
Hybrid Electric Vehicle (HEV)	Large (D)	
Internal Combustion Engine Vehicle (ICEV)	Sports (S)	
	Multi-purpose (M&J)	
	Light Commercial Vehicle (LCV)	

Table 2
Energy content and CO_2 emission factors. *Source*: Department of Energy and Climate Change (2011).

	Quantity	Energy (kW h)	Emission factors ($kgCO_2$)	
			Tailpipe	Well-to-wheel
Petrol	1 l	9.61	2.24	2.67
Diesel	1 l	10.60	2.55	3.11
Electricity	1 kW h	1	0	0.59

consumption measured in kilowatt-hours (kW h) is used as the reference unit. Each type of energy source is analysed based either on the carbon content of the fuel or the UK average grid electricity CO_2 intensity as appropriate (Howey et al., 2011); see Table 2.

During the 2011 FCC, electrical energy was measured either using the DA-EV1 or the DA-1 data logger provided by GEMS Ltd. Both data loggers recorded at a sampling frequency of 100 Hz. The analysis of the electrical 'tank-to-wheel' energy consumption needs to account for the battery losses to be comparable with fuel tank-to-wheel energy values. The equivalent electrical 'tank-to-wheel' energy consumption is the grid-to-wheel energy consumption (Wirasingha et al., 2012). This takes into account the charging efficiency η_{charge}, which for the 2011 FCC was assumed to be 93%, and the battery or coulombic efficiency $\eta_{battery}$, which was assumed to be 99%. This leads to:

$$E_{el} = \frac{\sum V(t) \times I(t) \times \Delta t}{\eta_{charge} \times \eta_{battery}} \tag{1}$$

The electrical energy is equal to the time integral of electrical power, which is the product of voltage V and current I. The two efficiency factors account for the battery and charging losses.

The energy stored per unit volume in conventional liquid fossil fuels is based on the calorific or heating value. The relative difference between the higher (HHV) and the lower heating values (LHV) based on volume is 5.2% for petrol and 6.4% for diesel (Department of Energy and Climate Change, 2011). As the HHV represents the maximum energy content stored in a fuel, the HHV is the preferred reference value over the LHV.

Diesel's volumetric energy density is 10% higher than that of petrol. The tank-to-wheel fuel energy consumption E_{fuel} can be calculated by dividing the vehicle's MPG trip reading by trip distance d_{FCC} in miles and multiplying this by the HHV_{fuel} of the fuel and the conversion factor between UK gallons and litres (4.546).

$$E_{fuel} = \frac{\text{MPG}}{d_{FCC}} \times HHV_{fuel} \times 4.546 \tag{2}$$

The vehicle's *MPG* was determined from the vehicle's on-board trip computer.

Driving behaviour refers to the individual speed, acceleration and traction behaviour of the vehicles. Twenty-seven of the participating vehicles were equipped with a global positioning system (GPS) receiver, which logged vehicle position with an accuracy of about 10 m, allowing for the generation of relative accurate speed and acceleration profiles for individual participants.

2. Theory

Following Newton's second law of motion, the longitudinal dynamics of a vehicle can be described by:

$$\underset{\text{Inertial F.}}{\underset{\uparrow}{M_v d/(dt) v(t)}} = \underset{\text{Traction F.}}{\underset{\uparrow}{F_t(t)}} - \underset{\text{Aerod. Drag}}{\underset{\uparrow}{(1/2\rho_{air}A_f C_d(v) v(t)^2}} + \underset{\text{Rolling Resistance}}{\underset{\uparrow}{m_v g \cos(\alpha) C_r(v)}} + \underset{\text{Climbing F.}}{\underset{\uparrow}{m_v g \sin(\alpha)}} + \underset{\text{Other losses}}{\underset{\uparrow}{I)}} \tag{3}$$

where m_v is the vehicle mass, v its velocity, ρ_{air} the air density, A_f the frontal area, C_d the drag coefficient, g the gravitational constant and α the road gradient.