



Shades of Green

Which low-carbon cars are
the most eco-friendly?

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May 2011

 RAC
Foundation

Foreword

The Royal Automobile Club's RAC Brighton to London Future Car Challenge was unique.



It showcased scores of the most advanced green vehicles in front of hundreds of thousands of eager spectators – the very people who must buy the cars on display if there is to be a green transport revolution. If the event achieved only one thing, it was to demonstrate that determining how drivers can realistically do their bit to save the planet is a complex matter. There is no simple answer, in part because we have yet to adequately define the question.

Is the most eco-friendly car the one which uses the least energy, or the one generating fewest CO₂ emissions? Should environmental impact be considered solely in relation to each journey a vehicle makes? What about the manufacture and distribution of fuel?

This report graphically illustrates how the green credentials of cars alter significantly depending on which angle you view them from.

For all of us who run a car this is not an academic exercise. Over the coming decades the make-up of the vehicle parc will change dramatically as manufacturers encourage us to buy their latest electric, hybrid or hydrogen-powered cars on the basis of their environmental performance.

Since the beginning of this year the Government has been offering grants of up to £5,000 for those early adopters who are ready to take the plunge and commit to buying an ultra-green car – that which produces 75 gCO₂/km or less.

For these pioneers there is plainly a lot to consider. Cutting through the jargon – CO₂ equivalents, tank-to-wheel, well-to-wheel – is only part of the problem. Even once a driver has made a theoretical choice, he or she is then likely to be confronted with the not insignificant practical problem of how to afford the object of their desire: while green cars might be cheap to run, many are anything but cheap to buy.

What happens when an owner finally wants to swap his now not-so-young automobile for something new? How will the used-car market price what is very much unproven technology? The questions are legion, but this report – and the event its launch coincides with – goes some way first to better defining them, and then answering them.

One thing is clear: when it comes to environmentally friendly vehicles, there's green and then there's *green*.

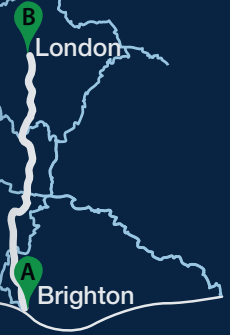
David Quarmby

A handwritten signature in dark ink, appearing to read 'David Quarmby'.

Chairman, RAC Foundation



The inaugural RAC Future Car Challenge took place on 6 November 2010 over a 57-mile route.



The event showcased 63 of the greenest vehicles on the road.

51 of the entrants allowed the organisers to collect data to analyse who used the least energy to complete the journey.

Entries were divided into three groups according to the power train:

1. pure electric
2. hybrids, including plug-ins, and hydrogen fuel cells
3. internal combustion engines emitting no more than 110 gCO₂/km

Measured in megajoules per kilometre on a tank-to-wheel basis, on average:

- Electric vehicles used 0.61MJ/km
- Hybrids used 1.16 MJ/km
- Diesels used 1.74 MJ/km
- The only petrol vehicle used 0.91 MJ/km
- And the only hydrogen fuel cell vehicle used 1.23 MJ/km
- In miles per gallon (petrol equivalent) this equates to 147 mpg for electric cars, 83 mpg for hybrids, 65 mpg for diesels, 95 mpg for the sole petrol car and 71 mpg for the hydrogen vehicle

Driving style, and vehicle and passenger weight, had a considerable impact on fuel consumption. Where the same make and model of vehicle was entered more than once, consumption ranged from 65 and 126 mpg for one of the hybrid models, and between 38 and 76 mpg for one of the diesel vehicles

Unsurprisingly electric and hydrogen vehicles performed best in CO₂ emission terms when measured on a tank-to-wheel basis, emitting zero carbon dioxide

But on a well-to-wheel measurement, things were rather different. On average:

- Hybrids emitted 103 gCO₂/km
- Electric vehicles emitted 105 gCO₂/km
- Diesel internal combustion engines emitted 147 gCO₂/km
- The petrol internal combustion engine vehicle emitted 81 gCO₂/km
- The hydrogen fuel cell vehicle emitted 112 gCO₂/km

The eco-credentials of electric cars depend on when they are charged. At night electricity is greener than during the day when more fossil fuels are burned

The observed levels of carbon emissions from the exhausts of the internal combustion engine vehicles were on average a quarter higher than European drive cycle figures

Fuel costs for the Challenge ranged between £1.44 and £7.42, with electric vehicles the cheapest to run

The Run

In its first year, the RAC Future Car Challenge attracted 63 entries from a wide range of manufacturers – from large to small volume as well as niche manufacturers. The vehicles were divided into three categories and in several cases there was more than one instance of a particular model in a given category:

Table 1: Power train types

	Power train	Number of vehicles (analysed: see section below)
Category 1	Pure electric vehicles	21 (16)
Category 2	Hybrid, plug-in hybrid, extended-range and hydrogen fuel cell vehicles	26 (20)
Category 3	Pure internal combustion engine (ICE) vehicles	16 (14)

Entrants had to agree to a set of regulations covering technical and competition requirements. All vehicles had to be road-legal, and vehicles in Category 3 were not permitted to exceed a maximum of 110 gCO₂/km as measured by the official European drive cycle. As for the competition, the organisers stipulated a minimum and maximum time for completing the course, and a half-way stop at Crawley.

Measuring energy consumption

Entrants wishing to take part in the competition for the most efficient vehicle prize had to agree to have their vehicle measured for energy consumption – this paper analyses 50 entries. The energy consumption was measured as follows.¹

The electric vehicles were fitted with a data logger situated between the battery pack and the electric motor which measured electricity use in kilowatt-hours (kWh). Although it would have been desirable to charge the vehicles to 100% battery capacity at the start and again at the finish for technical reasons concerned with accuracy of measurement; this was logistically impossible because of long charging times (up to five hours for this particular run) and the fact that the results were required immediately to determine the winner.

Hybrids and ICE vehicles were topped up to 100% with fuel at the start and finish to determine exactly how much was used during the run; an uncertainty factor was included to account for inaccuracies due to the refuelling process.¹ In addition to being refuelled, the plug-in hybrids were also fitted with data loggers as they are able to run exclusively on electricity for a considerable distance. The only hydrogen fuel cell vehicle that was measured had a fuel consumption display on the dashboard which indicated kilograms of hydrogen used for the trip.



Energy Consumption

To make a like-for-like comparison, energy consumption has to be expressed in a consistent metric: the chosen denominator is megajoules per kilometre (MJ/km) which can be easily converted into miles per gallon (mpg) petrol equivalent for ease of understanding.

Figure 1: Energy consumption per vehicle

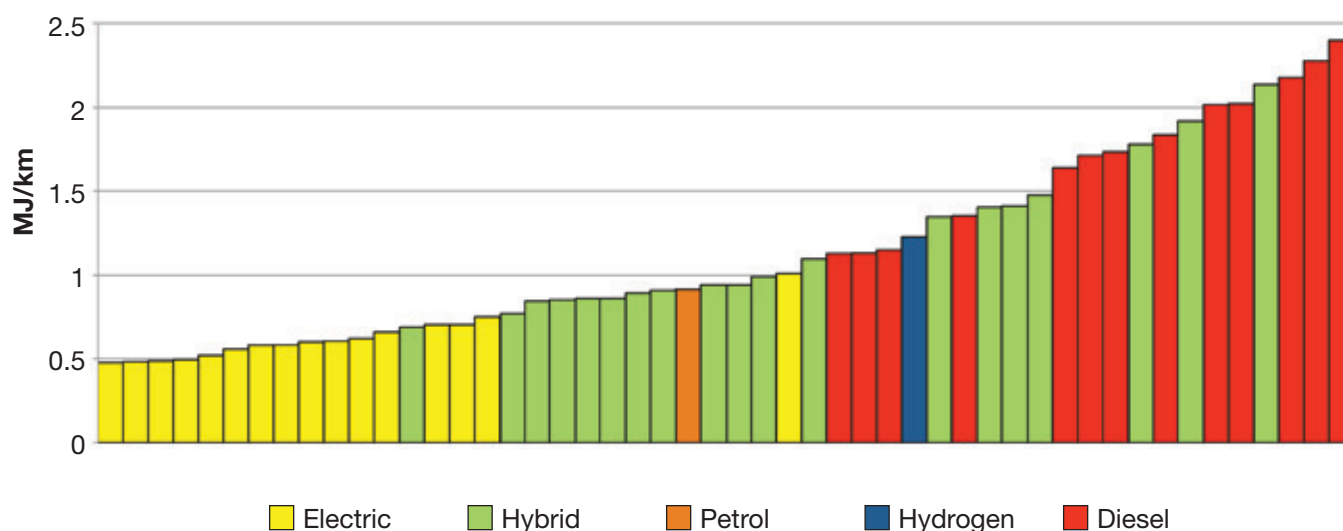


Figure 1 shows a clear picture: electric vehicles used the least amount of energy (averaging 147 mpg petrol equivalent), while hybrids made up the mid range (averaging 83 mpg) and diesel vehicles used the most (averaging 65 mpg), although there is some overlap, especially between the latter two categories. The average fuel economy of all vehicles was 80 mpg petrol equivalent. The only petrol-powered ICE car achieved 95 mpg, performing better than average and in fact also better than most hybrids thanks to its weight, while the only hydrogen fuel cell vehicle used 71 mpg petrol equivalent. To put this in perspective: the average UK car uses around 40 mpg and the average *new* car achieves 50 mpg.² The findings confirm expectations that the larger the degree of power train electrification, the more energy-efficient the vehicle.

It is noticeable that the figures vary by a factor of 5, with the most efficient vehicle achieving 182 mpg petrol equivalent and the least efficient achieving 36 mpg. Even within the categories, consumption varied by a factor of 3 for hybrids, 2.6 for ICE vehicles and 2 for electric vehicles.

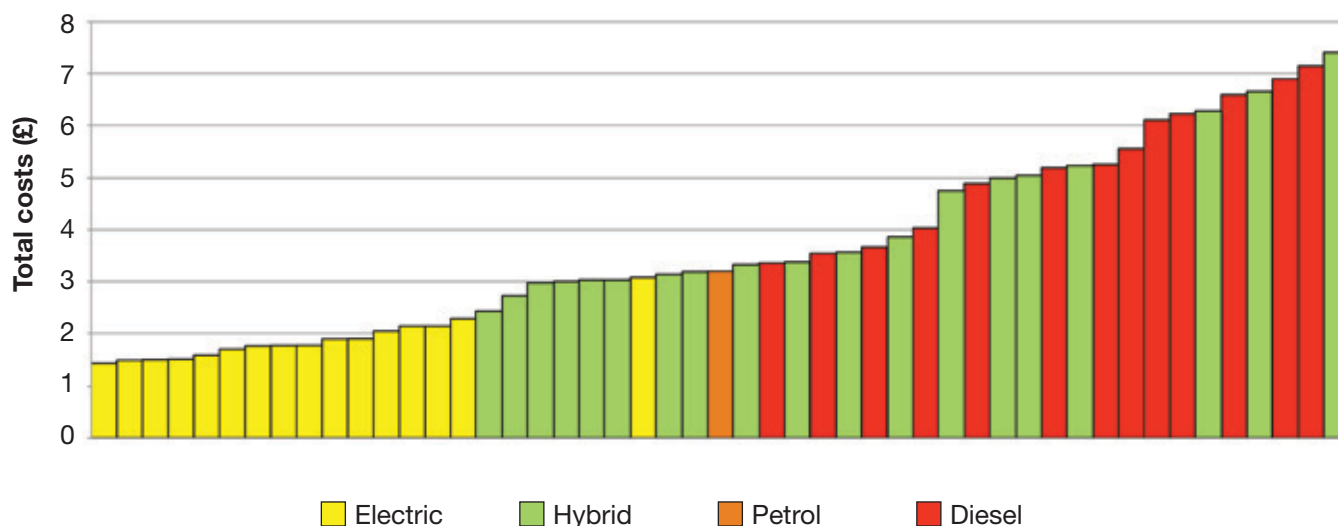
Although the variations can be explained by differences in engine technology, design and weight, driving style had a considerable impact on fuel economy. In the hybrid vehicle category, for example, fuel consumption varied between 65 and 126 mpg for one of the models, and between 59 and 113 mpg for one of the others. In the ICE category, it varied between 38 and 76 mpg for one of the models, and in the electric vehicle category the variation was less marked at between 116 and 124 mpg petrol equivalent.



Costs

Figure 2, which displays the fuel costs per vehicle for the run, shows a significant variation of between £1.44 and £7.42, and also reveals that electric vehicles were the cheapest to run, mainly because there is no tax on electricity. In the hybrid category, fuel costs varied by as much as £2.43 for one particular model, illustrating one of the benefits of ‘eco-driving’, i.e. steady acceleration and deceleration, early gear shifts, and so on.

Figure 2: Total fuel costs per vehicle for the run (November 2010 prices)



Note: the assumptions are £1.19 per litre of petrol, £1.22 per litre of diesel and £0.13 per kWh of electricity.^{3,4} Costs were not estimated for the fuel cell vehicle because there is currently no established price for hydrogen.

CO₂ Emissions

In order to obtain CO₂ emission figures, the energy consumption results had to be converted using certain factors, as the CO₂ intensity of one unit of energy varies between the different fuel types (electricity, petrol, diesel and hydrogen).

Before converting the figures, however, it is necessary to distinguish between emissions from the exhaust – ‘tank-to-wheel’ emissions – and emissions over the life cycle – ‘well-to-wheel’ emissions. The latter comprise tank-to-wheel emissions plus ‘well-to-tank’ (or ‘indirect’) emissions which are defined as ‘those... emitted prior to the use of a fuel/energy carrier (or in the case of electricity, prior to the point of generation), i.e. as a result of extracting and transforming the primary energy source (e.g. crude oil) into the energy carrier (e.g. petrol)’⁵:

$$\text{Well-to-Tank} + \text{Tank-to-Wheel} = \text{Well-to-Wheel}$$

An even more comprehensive analysis would take account of ‘embedded’ emissions arising from vehicle production and scrappage, but this was beyond the scope of this analysis as the data is not readily available.

The rationale behind this distinction is that while an analysis of well-to-wheel emissions is crucial for understanding a vehicle’s impact on global warming, a consideration of

only tank-to-wheel emissions highlights the often-ignored issue of local air quality. Road vehicles, particularly diesels, are the main emitters of pollutants in urban areas, and are estimated to cause 50,000 premature deaths per year. In fact, the UK could face sanctions of the order of £300 million from the EU for continuously breaching its national air quality targets.⁶ This is a clear benefit of electric vehicles, which have zero emissions at the exhaust, and hydrogen fuel cells which emit only water vapour.

Tank-to-wheel CO₂ emissions

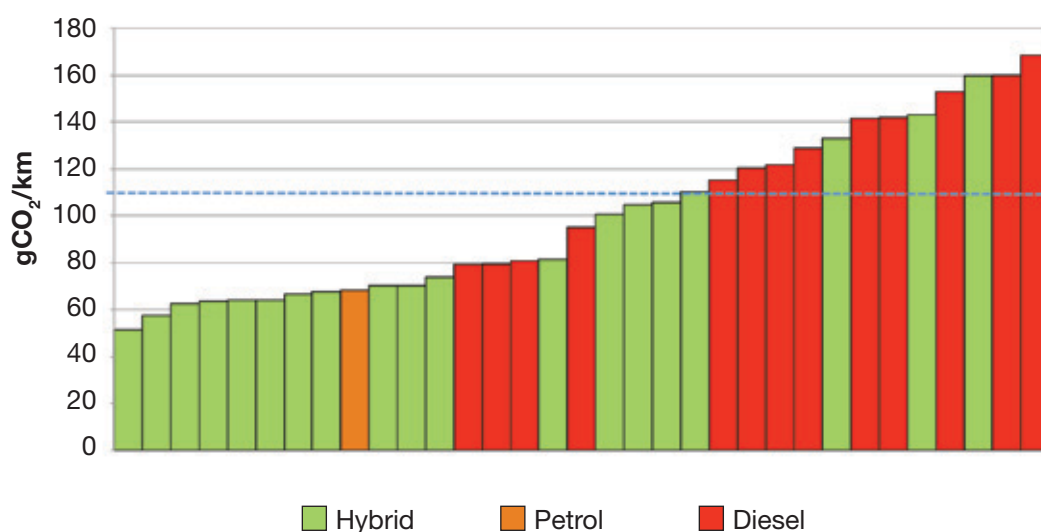
As electric vehicles have no emissions at the exhaust, and hydrogen fuel cell vehicles emit merely water vapour, tank-to-wheel emissions only have to be calculated for all the vehicles that used petrol or diesel, i.e. all ICE vehicles and hybrids. The conversion is straightforward, as petrol and diesel have a specific volumetric energy content and CO₂ intensity, so emissions can be calculated directly from the amount of energy used. While the former was provided by the fuel supplier, official government estimates were used for the CO₂ intensity per litre⁵:

Table 2: Tank-to-wheel CO₂ conversion factors

	CO ₂ emissions (g/MJ)	Assumption
Petrol	74.7	Calorific value of 30.8 MJ/litre and CO ₂ emissions of 2.30 kgCO ₂ /litre
Diesel	70.3	Calorific value of 37.6 MJ/litre and CO ₂ emissions of 2.64 kgCO ₂ /litre

Using these factors gives the following results: hybrids, averaging 87 gCO₂/km, performed better than ICE vehicles, which on average emitted 120 gCO₂/km. Most hybrids emitted less than 75 gCO₂/km, some of them even as little as 50 gCO₂/km. The only petrol ICE vehicle entry emitted 68 gCO₂/km, 22% less than the average hybrid.

Figure 3: Tank-to-wheel CO₂ emissions



Two points are noteworthy: the variation in emissions performance between different vehicle technologies within the same category, and the divergence between officially measured and

actual emissions. Whereas the variation between the different models in the ICE vehicle category is over twofold, the variation within the hybrid category is as high as threefold between the different models. This confirms one of the King Review's findings that buying best-in-class vehicle models can reduce emissions by 25% compared to the class average⁷ – in this case even more.

The second point is that although the entry regulations specified a maximum of 110 gCO₂/km for ICE vehicles as measured by the official European drive cycle (indicated by the dotted blue line in Figure 3), 9 out of 14 entries actually exceeded this threshold despite the fact that the nature of the event encouraged eco-driving. Equally, some of the ICE vehicles and in fact the majority of hybrids performed better than was officially claimed.

Well-to-wheel CO₂ emissions

In the case of electric vehicles, well-to-wheel emissions depend on the assumptions made about 'grid carbon intensity' – this refers to the CO₂ content of one unit of electricity from the plug commonly measured in grams of CO₂ equivalents per kWh (gCO₂e/kWh). The measure is expressed in CO₂ equivalents as it not only takes into account CO₂ emissions but also methane and nitrous oxide, weighted according to their global warming potential.⁵

The difficulty arises because grid carbon intensity varies: during the day it is high since electricity is produced from more abundant and carbon-intensive resources such as gas and coal to meet higher demand, while at night it is less carbon-intensive because lower demand means that a greater proportion of supply can be met by electricity generated from nuclear baseload.⁸

There is also the issue of whether to use an average emissions factor (AEF) or marginal emissions factor (MEF). The AEF takes into account the average electricity mix and associated emissions over a longer period of time. It typically fluctuates between 470 gCO₂/kWh at night and 550 gCO₂/kWh during the day^{9,10}; the Government uses a rolling average of 542 gCO₂/kWh.⁵ The MEF, on the other hand, captures the emissions from the 'marginal' power plant. The rationale is that rather than looking at the average, it is necessary to take into account the emissions from generating the extra electricity that is specifically used for an additional load. Currently the MEF is around 690 gCO₂/kWh⁸; it is higher than the AEF because peak demand is met through the use of more abundant, carbon-intensive sources such as coal and gas. This paper will not argue the case for one over the other – instead, it will illustrate the implications of assuming different factors at different times of day.



Indirect emissions add 75 gCO₂e/kWh to the rolling average of 542 gCO₂/kWh, giving a figure of 617 gCO₂e/kWh for electricity, adding also around 20% to the petrol and diesel factors used to calculate tank-to-wheel emissions^{5,11}:

Table 3: Well-to-wheel CO₂ conversion factors

	CO ₂ emissions (g/MJ)	Assumption
Petrol	88.7	Calorific value of 30.8 MJ/litre and CO ₂ emissions of 2.73 kgCO ₂ e/litre ⁵
Diesel	84.5	Calorific value of 37.6 MJ/litre and CO ₂ emissions of 3.18 kgCO ₂ e/litre ⁵
Electricity	171.4	2008 UK grid rolling average of 617 gCO ₂ e/kWh ⁵
Hydrogen	91.7	Calorific value of 120 MJ/kg, produced from steam-reformed natural gas ¹

Using these official conversion factors means that hybrids performed best, ranging from 61 to 190 gCO₂e/km, averaging 103 gCO₂e/km. Electric vehicles made up the mid range, with emissions ranging from 82 to 173 gCO₂e/km and having an average of 105 gCO₂e/km. Emissions of diesel ICEs varied between 95 and 203 gCO₂e/km, with an average of 147 gCO₂e/km. The petrol ICE entry emitted 81 gCO₂e/km, whereas the hydrogen fuel cell vehicle emitted 112 gCO₂e/km.

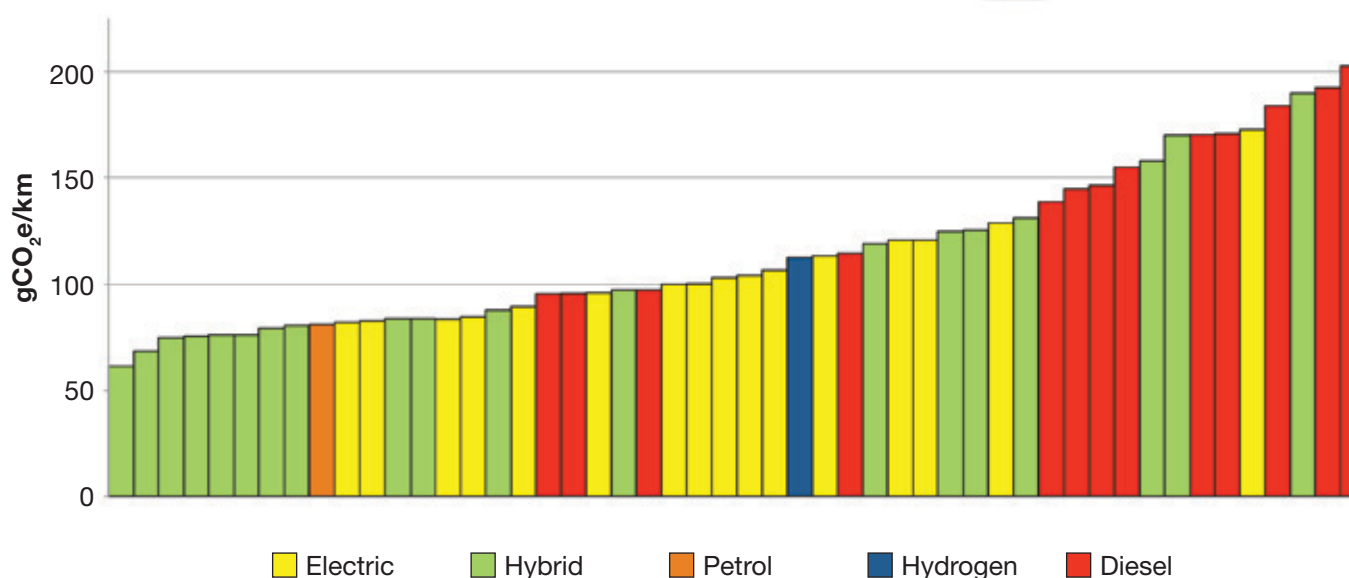
Figure 4: Well-to-wheel CO₂e emissions using government conversion factors

Figure 5 shows the 'worst case scenario' for electric vehicles today – assuming that they are charged at peak hours, i.e. the early evening, at which time grid carbon intensity is assumed to be 690 gCO₂/kWh (MEF). Figure 6, on the other hand, illustrates the 'best case scenario' in which electric vehicles are charged at night using lower carbon electricity, when grid carbon intensity is 470 gCO₂/kWh (AEF). The results differ significantly and illustrate the importance of encouraging charging at night – which is most likely to be done at home – through the use of tariffs which maximise CO₂ reduction and minimise fuel costs because of cheaper electricity.

Figure 5: Well-to-wheel CO₂ emissions using MEF

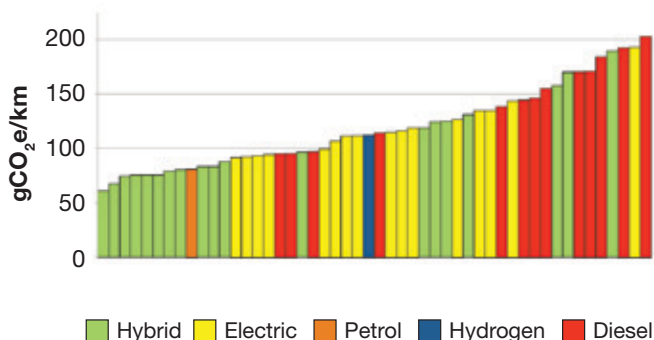
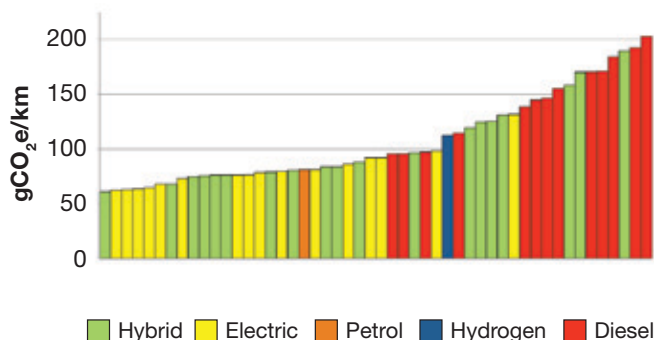


Figure 6: Well-to-wheel CO₂ emissions using night-time AEF



Conclusions

Although the energy and CO₂ results from the RAC Future Car Challenge are only indicative and should not be regarded as universally valid, they do confirm certain expectations.

First and foremost they show there is **currently no clear winner** in the battle for the title 'most eco-friendly car'. Electric vehicles used the least amount of energy and, along with hydrogen fuel cell vehicles, produced zero emissions from the exhaust, but fared less favourably in terms of overall CO₂ emissions compared to certain hybrids. And although diesel vehicles were generally the least efficient, the best ones were able to stand up against their hybrid and electric counterparts, underlining the fact that there is still considerable potential for improvement of conventionally-powered vehicles.

It is plain that electric vehicles are only as green as the electricity they use, and that their CO₂ performance varies depending on the **carbon content of electricity**. Their environmental credentials will improve as national and EU regulation forces the decarbonisation of the electricity supply. To meet the UK's legally binding greenhouse gas reduction targets (34% by 2020 and 80% by 2050, both relative to 1990), and to implement the EU's directive on renewable energies, the grid carbon intensity will have to be halved over the next decade¹² and become virtually zero by the middle of the century.

There was considerable **variation in fuel consumption and CO₂ performance** among and within the different vehicle categories. While the variation is largely explained by the use of different engine technologies and weight, the results also show that **driving style** can make a significant impact on fuel consumption and hence CO₂ emissions, evidenced by the variation in performance among the same models. In one case fuel economy ranged between 65 and 126 mpg which amounted to a difference in fuel costs of £2.43.

Finally, the results also revealed a **divergence between real-world and claimed fuel consumption/CO₂ emissions performance** as measured by the official New European Drive Cycle (NEDC) – a simulated drive cycle with steady engine accelerations and decelerations. This is illustrated by the fact that the majority of internal combustion engine vehicles actually exceeded the 110 gCO₂/km requirement as specified in the entry regulations. Equally, however, some of the ICE vehicles and several hybrids performed better than was officially claimed, confirming concerns over the appropriateness of the NEDC in giving realistic performance figures.

Acknowledgements

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The Royal Automobile Club Foundation for Motoring Limited is a charity which explores the economic, mobility, safety and environmental issues relating to roads and responsible road users. Independent and authoritative research, carried out for the public benefit, is central to the Foundation's activities.

Overall winner: VW Golf Blue-e-Motion

Category 1: Pure electric vehicles

Ford Transit Connect Electric
Liberty E-Cars Electric Range Rover
Liberty E-Cars Electric Range Rover
Lotus Elise S1 Electric
MaxEV VW Caddy Maxi
MG MG-F Electric
Mini E Electric
Mitsubishi i-MiEV
Nicholson McLaren Citroën Nemo Van
Nicholson McLaren Citroën Nemo Van
Nissan Leaf

Proton Saga Electric
smart electric drive
Tata Indica Vista
Tesla Roadster Sport
Tesla Roadster Sport
Tesla Roadster Sport
Tesla Roadster
Vince Nemesis
VW Golf Blue-e-Motion
Zytek Mercedes Benz Vito Taxi

Category 2: Hybrid, plug-in hybrid, extended-range and hydrogen fuel cell vehicles

Honda CR-Z Hybrid
Honda CR-Z Hybrid
Honda FCX Clarity
Mercedes Benz B-Class F-Cell
Proton Exora E-REV
Toyota Auris Hybrid
Toyota Auris Hybrid
Toyota Auris Hybrid
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Toyota Auris Hybrid
Toyota Auris Hybrid
Toyota Auris Hybrid

Toyota Auris Hybrid
Toyota Auris Hybrid
Toyota FCHV-ADV Fuel Cell Highlander
Toyota Prius Hybrid (1st generation)
Toyota Prius Hybrid (2nd generation)
Toyota Prius Hybrid (2nd generation)
Toyota Prius Hybrid (3rd generation)
Toyota Prius Hybrid (3rd generation)
Toyota Prius Hybrid (3rd generation)
Toyota Prius Hybrid (3rd generation)
Toyota Prius Hybrid (3rd generation)
Toyota Prius Plug-In Hybrid
Toyota Prius Plug-In Hybrid
Vauxhall Ampera E-REV

Category 3: Pure internal combustion engine vehicles

BMW 320d EfficientDynamics
BMW 320d EfficientDynamics
Ford Fiesta 1.6 TDCi/DPF ECONetic
Ford Fiesta Van 1.6 TDCi ECONetic
Ford Focus 1.6 TDCi ECONetic
Gordon Murray Design T.25
Mini Cooper Diesel
Renault Clio 1.5 dci

Renault Clio 1.5 dci
Skoda Fabia Greenline II
Vauxhall Astra 1.3 CDTi ecoFlex
Vauxhall Corsa 1.3 CDTi ecoFlex Start/Stop
Vauxhall Corsa 1.3 CDTi ecoFlex Start/Stop
VW Golf BlueMotion
VW Golf BlueMotion
VW Polo BlueMotion

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