Battery electric vehicles, hydrogen fuel cells and biofuels. Which will be the winner?

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Introduction

Background

A highly developed road transport system for passengers and goods is an essential component of all major industrial economies. Indeed, road transport activity and gross domestic product (GDP) have historically shown a strong correlation, although a slight decoupling has been observed in recent years in industrialised countries. Road transport is also responsible for a significant and growing share of global primary energy consumption, a consequence of its pervasiveness and high energy intensity. Future energy demand from road transport worldwide is expected to continue growing steadily under a business-as-usual scenario, mainly driven by economic development in large countries such as China and India [1].

Road transport today is dominated by oil-derived fuels and internal combustion engines, which makes it unsustainable both economically and environmentally. In particular, oil price volatility and supply disruptions represent a serious threat to road transport affordability and reliability, the lack of which can affect GDP. Moreover, the use of oil-derived fuels in internal combustion engines is inherently coupled with emissions of greenhouse gases (GHG) as well as of regulated air pollutants such as fine particulate matter (PM_{10}), volatile organic compounds (VOCs) and nitrogen oxides (NO_X).

Addressing all these issues simultaneously will ultimately require moving away from oil-derived fuels and conventional internal combustion engine powertrains, replacing these with low-carbon, renewable fuels and alternative low-emission, high-efficiency powertrains. The main technological options that are currently being considered are: improved internal combustion engine vehicles (ICEVs) powered by biofuels, battery electric vehicles (BEVs) and hydrogen fuel cell vehicles (FCVs). Hybrid solutions are also possible, such as battery electric vehicles equipped with range extenders (PHEVs), be they internal combustion engines or fuel cells. All three fuels considered (i.e.: biofuels, electricity and hydrogen) are in principle compatible with the objectives of moving away from oil. They may also significantly reduce GHG emissions from road transport, depending on the primary energy sources and the processes used for their production. Only electricity and hydrogen have zero emissions of air pollutants at point of use. However it should be noted that biofuels that are oxygenates (e.g. ethanol) may also help reduce emissions from combustion [2, 3].

The rate at which these alternative fuels and powertrains are introduced as substitutes for conventional road transport fuels and powertrains should ideally be compatible with achieving international energy and environmental policy goals. It is also desirable that these goals are achieved at a minimum cost to society. Planning the transition based on predictions of “when we will run out of cheap oil” is problematic because oil price forecasts and reserve estimates are affected by considerable uncertainty [4, 5]. Even without these motivations, reducing external costs such as air pollution in urban areas (which can exacerbate respiratory illnesses and is cause of premature death) has clear societal benefits. From all these perspectives, the sooner alternative transport fuels can become competitive with oil-derived fuels and displace them the better.

Deploying alternative vehicles and fuels at a sufficient rate to meet the 2050 target of reducing greenhouse gas emission (GHG) by 80% as indicated by the Intergovernmental Panel on Climate Change (IPCC) [6] is a formidable challenge, the scale of which is illustrated by the IEA’s Blue Map scenario (see Figure 1 below). It is unlikely that market forces alone will be able to organically deliver this complex transition in the required timeframe. Therefore if political aspirations are to be met, policy interventions will be required in order to stimulate and manage the transition effectively.

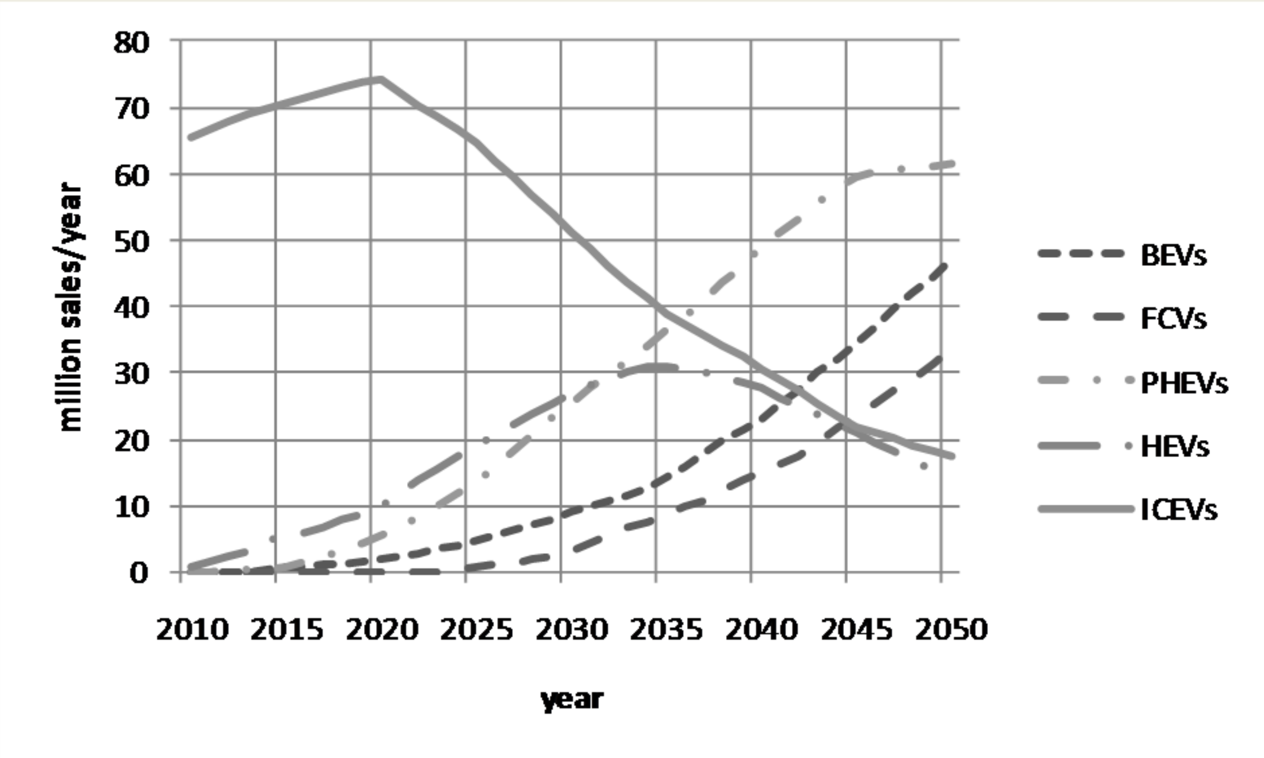

Figure 1: Illustration of a possible uptake scenario for electric-drive vehicles (Battery Electric Vehicles – BEVs; Fuel Cell Vehicles – FCVs; Plug-in Hybrid Vehicles – PHEVs; Hybrid Electric Vehicles – HEVs;), progressively replacing conventional Internal Combustion Engine Vehicles – ICEVs, that is compatible with meeting the IPCC's 2050 GHG emission reduction targets (adapted from the IEA BLUE Map scenario [1]).

Aim and structure of the paper

Designing effective strategies for the development and large-scale deployment of alternative fuels and vehicles requires, *inter alia*, a good understanding of the role that each one of these technologies is capable of playing in a future sustainable transport system.

In recent years, seven major studies [1, 7-12] have been devoted to assessing and comparing the alternative fuel and vehicle options that are regarded as most promising. These studies have generated and synthesised a tremendous amount of knowledge, but, because they have adopted different approaches and assumptions, they have sometimes also come to different conclusions. It is difficult, therefore, to make full use of this and the vast body of supporting knowledge in the peer reviewed literature, and this is a particular problem for non-expert policy community.

The structure of the paper is as follows. In Section 2, these studies are critically reviewed. This review aims to build a concise picture of the state of the art of this field of research, highlighting strengths and weaknesses of existing studies.

Recent research carried out by the authors is then presented that illustrates the impact that different approaches and assumptions can have on the results of comparative analyses of alternative fuels and vehicles. In particular, Section 3 describes the technologies under analysis and their potential for future performance improvement and cost reduction; previous work by the authors [13] is extended to include bioethanol in combustion engines. The spreadsheet tool used for the analysis, and the underlying assumptions used are all described. We place our study in year 2030 and we assume that all technologies compared are fully developed and mass produced by then. This assumption is necessary if the 2050 decarbonisation targets are to be achieved, due to the average lifetime of a passenger car being around 10-15 years, which limits the rate at which technology substitution can occur.

In Section 4 results of the assessment are presented and discussed. In particular, the effects on the final results of assumptions made and methods used are probed. Finally, conclusions and recommendations are provided in Section 5.

Critical review of selected recent comparative studies of alternative fuels and vehicles

Since the first oil price shock in the 1970s a vast number of studies has been devoted to assessing technical, economic and environmental impacts of alternatively fuelled vehicles. Studies have typically been motivated by supporting the introduction of specific alternative technologies, therefore early ones mainly focused on battery electric vehicles, while later on the emphasis shifted towards hydrogen fuel cell vehicles. More recently, biofuels have attracted considerable interest and we have also witnessed the resurgence of interest in electric vehicles, both pure battery vehicles and plug-in hybrids. Therefore, while earlier studies investigating techno-economic and environmental performance of alternative fuels and vehicles largely considered each option in isolation, in the last few years a number of studies have been published which seek to compare several possible technologies at the same time.

Even though this field only matured relatively recently, the literature comparing alternatively fuelled vehicles is already quite vast. Therefore this paper focuses on studies selected because they meet the following criteria: a) that they compare most if not all of the alternative vehicle and fuel options; b) that they are high profile and hence can potentially influence policy makers; c) that they are the result of the work of a group of experts and have been either peer-reviewed or extensively validated by industry. Other studies are commented on as and when they are relevant to the discussion.

The studies that meet these criteria are listed in Table 1. To aid our discussion we have divided the studies into two groups: “Well-to-Wheel studies” and “techno-economic, energy and environmental impact assessment studies”. Sections 2.1 and 2.2 discuss each group of studies in turn. In Section 2.3 we then compare and contrast the main results of the studies, the methods used and their limitations. The aim is to draw a high-level picture of the state of the art of research in this area and to highlight remaining gaps in knowledge.

Table 1. Comparative studies reviewed in this paper and their main characteristics. Studies are listed in reverse chronological order

Ref #	Study authors	Year	Models used	Technologies compared	Vehicle types/ driving cycles	Time horizon	Region
10	McKinsey/ powertrain alliance	2010	Ad-hoc techno-economic models	Advanced (hybridised) ICEs, PHEVs, BEVs and FCVs	Key European segments: A/B (small), C/D (medium), J (SUV); average fleet values, no single car model. Distance weighted average of ECE-15 and EUDC cycles.	2050	Europe
1	IEA	2009	IEA Mobility Model (MoMo) and Database	ICEs, HEVs and PHEVs using conventional & synthetic fossil fuels, biofuels and hydrogen; BEVs and FCVs	Typical OECD passenger light duty vehicles	2050	World
11	NHA	2009	ANL GREET 1.8a (WtT); own vehicle simulation tool (TtW); US DoE H2A model (H_2 infrastructure)	gasoline HEV & PHEV, ethanol PHEV, FCV, FCPHEV, BEV	Typical US passenger car; modified EPA driving cycle	2100	US
12	MIT	2008	ANL GREET (WtT); ADVISOR (TtW); MIT own fleet development model	ICE vehicle with reduced weight and performance, and improved ICE (downsized, turbocharged), HEV, biofuels, PHEV, BEV, FCV	Typical 2005 US passenger car (Toyota Camry 2.5L) and light truck (Ford F-150 4.2L). Several standard driving cycles	2035	US; comparison to western Europe
9	JRC	2007	LBST E^2 Database (WtT); ADVISOR (TtW)	ICEV, HEV, FCV; gasoline & diesel, CNG, LPG, synthetic liquid fuels, biofuels, H_2	Compact 5-seater passenger car (Volkswagen Golf). Standard European driving cycle (NEDC)	2010+	Europe
8	GM/ LBST	2002	LBST E^2 Database (WtT); GM proprietary vehicle simulation tool (TtW)	ICEV, HEV, FCV; gasoline & diesel, CNG, LPG, synthetic liquid fuels, biofuels, H_2	2002 Opel Zafira with projected 2010 powertrain 1.8L gasoline ICE, 5 speed manual transmission. Standard European Driving Cycle (NEDC)	2010	Europe
7	GM/ ANL	2001, 2005	ANL GREET (WtT); GM proprietary vehicle simulation tool (TtW);	ICEV, HEV, FCV; gasoline & diesel, CNG, LPG, synthetic liquid fuels, biofuels, H_2	Full-size GM pick-up truck (model year 2010). US combined urban and highway driving cycle	2010	US

Well to Wheel studies

The first group of recent studies to rigorously compare several different types of alternative fuels and powertrains are the so-called "Well-to-Wheel" (WtW) studies. WtW analysis is a system approach to assessing the energy consumption and GHG emissions associated with different fuels and propulsion systems; it takes into account every stage of the process, from fuel production ("well") to its end use in a vehicle ("wheel"). However, unlike lifecycle analysis (LCA), WtW studies usually do not take into account the energy and emissions involved in constructing and decommissioning fuel production and delivery infrastructure, or in manufacturing and disposing of the vehicles. WtW studies usually cover all fossil-fuel options (i.e.: liquid fuels derived from oil, gas and coal, and gaseous fuels such as compressed natural gas) as well as the main biofuel and hydrogen pathways. Powertrain options considered typically include all main types of internal combustion engines (including hybrids) and also hydrogen fuel cells. For comparative purposes, vehicles are modelled based on one shared platform, chosen as the "typical" car in the region considered. Regardless of the powertrain type, all vehicles modelled have to meet certain minimum performance requirements (in terms of speed, acceleration and range, to name the most important ones) which are characteristic of today's ICEVs. Vehicle fuel consumption and emissions are estimated over standard driving cycles using a vehicle simulation tool. It is important to note that WtW studies often exclude pure battery electric vehicles; this is due to the difficulty of modelling a practically viable BEV that can achieve the same level of performance of a conventional ICEV, particularly with respect to range.

In order to reduce uncertainty, WtW studies generally use technology data which are either current or projected in the near future; so the energy efficiency and carbon emissions results they generate are reasonably accurate. However, because they are often based on near-term technology, these studies do not allow a comparison of alternative fuel and vehicle technologies in a future when they are fully developed. The main strength of WtW studies is that, by comparing a large number of fuel production and delivery chains, they allow us to identify which pathways are more promising to produce a certain fuel and also what uses of primary energy sources in road transport are more efficient. Well-known WtW studies are the General Motors (GM)/Argonne National Laboratory (ANL) study for North America (first published in 2001 and then extended and updated in 2005) [7], and its sister study for Europe by GM/L-B-Systemtechnik GmbH (LBST) which was published in 2002 [8]. Then followed the JRC/EUCAR/CONCAWE study [9] which was first published in 2003, then updated in 2005 and again in 2007. The latter has become the WtW study of reference for Europe and its results continue to be used as inputs into comparative studies of road transport vehicles and fuels. Apart from the different input data used (in the GM/ ANL these are representative of the US situation, while the other two studies focus on Europe), it must be noted that different Well-to-Tank (i.e.: fuel chain) and Tank-to-Wheel (i.e.: vehicle simulation) models are also used across the studies; see Table 1 for more details.

WtW studies in general form the basis for assessing the impacts of future fuel and powertrain options, particularly in terms of energy use and GHG emissions. However it is important to note that results of these studies need to be further evaluated in the context of the broader feasibility, cost and market potential of the technologies; these important aspects are only addressed to a limited extent in WtW studies. Finally, another limitation of WtW studies is that they only use one vehicle type and one driving cycle, which are not necessarily representative of the average vehicle population and usage profile and which cannot be extrapolated to other market segments. Therefore WtW studies do not capture the complexity of the passenger car market.

Techno-economic, energy and environmental impact assessment studies

The other studies that we have selected for review (see Table 1) are grouped under this broad category. These studies often have an element of WtW analysis, or even LCA, as part of a broader techno-economic, energy and environmental impact assessment. In fact they can be seen as an evolution of WtW studies because they not only compare fuel/powertrain chains on the basis of the energy consumption and emissions of a single vehicle, but they also use regional or global fuel and vehicle uptake scenarios in order to assess the energy security, environmental and economic implications of the large-scale adoption of the vehicle types considered. It is for this reason that the studies also focus on a much longer time horizon than WtW studies; the fuels and vehicles are generally compared in a future when they are technically fully developed and mass produced. Therefore the studies also allow to explore different possible fuel and powertrain portfolios that are potentially capable of meeting the policy objectives of reducing oil dependency, mitigating climate change and improving urban air quality. Here follows a brief discussion of some of the most significant studies which were published in recent years.

MIT study "On the road to 2035"

In 2000 the Massachusetts Institute of Technology (MIT) issued a report called "On the road in 2020" [14]. The report compared conventional fuels and vehicles with alternative options and assessed the potential for reducing fuel consumption and GHG emissions in the US based on an LCA approach. The report also addressed costs in 2020 and other impacts of the new technologies on key stakeholders groups. The analysis was mainly based on published data, in order to guarantee transparency, and uncertainties in future projections were duly accounted for. Since then work continued and in 2008 MIT published the report "On the road in 2035" [12], which updates and extends the previous report and looks at a slightly longer timeframe. Again the emphasis is on the US, but comparisons with western European countries are also made.

The MIT study uses a number of tools and methods with the aim of identifying fuel/ powertrain options that can lead to a significant reduction of fuel use and GHG emissions, in 2035 and beyond. Firstly, all potentially promising fuel, powertrain and vehicle technologies are reviewed and a subset of them is selected. Then, for all selected fuel options, lifecycle energy use and emissions are estimated using GREET, an LCA tool for transport fuels developed at the Argonne National Laboratory (ANL) in the US. Vehicle fuel consumption is assessed using standard driving cycles in ADVISOR, a vehicle simulation tool originally developed at the National Renewable Energy Laboratory (NREL) and now commercialised by AVL. Combining the two, lifecycle fuel consumption and GHG emissions are estimated for each vehicle/fuel combination. Following this, additional costs of alternative vehicle and fuel technologies are estimated, relative to the reference case of a gasoline-fuelled advanced ICE vehicle. The cost data are then fed into a vehicle fleet model, in order to derive plausible uptake rates of different alternative vehicles and fuels. Combining vehicle uptake scenarios with lifecycle energy consumption and GHG emissions, the impact of each vehicle/ fuel option on overall fuel consumption and GHG emissions in the US are estimated. Finally, scenarios are developed which involve portfolios of vehicles and fuels, and their implications in terms of fuel use and GHG emissions are quantified.

The MIT study essentially concludes that potential exists in the US for significantly decreasing fuel consumption and GHG emissions by 2035, at relatively low cost to the consumer. This can be achieved mainly by improving the efficiency of conventional internal combustion engine powertrains and by reducing the weight, size and performance of vehicles. It is useful to note that, unlike the US, in Western Europe many of the possible efficiency gains have already been achieved to a significant extent, so their future potential is much more limited.

According to the MIT study, plug-in hybrids and biofuels may also play a role in 2035, although both technologies face hurdles and limitations. Indeed, if aggressive penetration of downsized, lightweight hybrid vehicles, together with plug-in hybrids and biofuels, is achieved, then reducing fuel consumption by 40-50% compared to 2008 levels in the US is potentially feasible. As for FCVs and BEVs, they are not expected to contribute significantly to reducing fuel consumption and GHG emissions by 2035. This is because they are likely to continue to be characterised by a high capital cost penalty, which will only be offset by their relatively higher efficiency compared to hybrid ICE vehicles under high gasoline price scenarios. It is however recognised that FCVs and, to a lesser extent BEVs, may have a role to play in the longer term and that current RD&D efforts should be sustained in order for these vehicles to be on the road in significant numbers by 2050.

The results of the MIT study are particularly significant in the market and policy context of the US, but perhaps less so in a European context where the average fuel economy of passenger cars is already much higher and where very ambitious GHG emission reduction targets are expected to be a stronger driver towards electrification of passenger vehicle powertrains than in the US. Moreover, only two vehicle types are modelled, an average US passenger car and a pickup van, and US standard driving cycles are used. This means that the complexity of the passenger car market and the different uses that are made of different vehicle segments are not entirely captured by the study. Finally, assumptions made for hydrogen and electricity production, both based only on fossil feedstock, do not reflect their full potential as low-carbon transport fuels.

<u>NHA "The Energy Evolution: An Analysis of Alternative Vehicles and Fuels to 2100"</u>

In 2009 the US National Hydrogen Association (NHA) published a report titled: "The Energy Evolution: An Analysis of Alternative Vehicles and Fuels to 2100" [11]. The report is largely based on previous research and modelling activities, most of which is also published in peer-reviewed journals [15]. Moreover, the report sees the involvement of a number of industrial organisations and has been independently reviewed by experts at the US Department of Energy (DOE) and at the National Renewable Energy Laboratory (NREL), among others. Therefore the objectivity of the study is ensured, despite it being issued by an organisation promoting the commercialisation of hydrogen and fuel cell technologies in particular.

The NHA study analyses key alternative fuel and powertrain options: ICE hybrids and plug-in hybrids (fuelled by both conventional fuels and biofuels), battery electric and fuel cell vehicles. It assesses the impact on the environment, energy security and the economy of these alternative fuels in the US until 2100, and hence their ability to simultaneously meet the long-term energy and environmental policy goals of decarbonisation, energy security and urban air quality. Similarly to the MIT study, the NHA study also uses the GREET model coupled with a vehicle simulation tool. However, in the NHA study the vehicle uptake scenarios are exogenous, as opposed to being endogenously generated by a fleet model as in the MIT study. The scenarios are used as an input to a dynamic model, which endogenously simulates the evolution of the vehicle technology over time. The model therefore assesses oil demand, emissions of GHGs and air pollutants from passenger cars in the US as they evolve over time, as a function of vehicle uptake but also of the development of vehicle technology. As for the economic impacts on society, these are essentially estimated as the sum of the fuel infrastructure costs and the capital and operating costs of the vehicles. Underlying assumptions of the study are that key techno-economic targets for batteries and fuel cells are met. Hydrogen infrastructure costs are estimated based on the H2A model of the US DOE. Vehicle cost data assuming mass production are based on Kromer and Heywood [16], hence they are broadly consistent with the MIT study.

Overall, the NHA study uses a similar approach and largely consistent data to the MIT study. Therefore it is not surprising that some of the results are comparable. However, the NHA study is also complementary to the MIT, as it looks at a much longer time horizon.

Results of the NHA study suggest that, of all possible options, only battery electric and hydrogen fuel cell vehicles are able to simultaneously meet energy security, air quality and GHG emission reduction targets on their own. The other options can indeed form part of a portfolio of fuel and vehicle technologies and as such can contribute to reducing emissions of GHG and other pollutants as well as oil dependency; however they are destined to be eventually replaced by either BEVs or FCVs if the long-term energy and environmental policy targets are to be met in full. Interestingly, fuel cell plug-in hybrids (FCPHEVs) are initially also considered but they are dismissed due to the relatively high carbon intensity of the US electricity mix, which makes their WtW carbon emissions higher than those of pure FCVs. The study also finds that ethanol-fuelled PHEVs don't go near meeting the three policy targets previously mentioned.

In the NHA study alternative scenarios are built where either FCVs or BEVs eventually dominate the passenger car market. A detailed technical analysis is also carried out, which concludes that BEVs can only compete with FCVs if we consider vehicles with a range of 100 miles or less. BEVs that are capable of longer ranges are bound to be much heavier than the corresponding FCVs. The weight penalty directly translates into worse performance and comfort, which can affect customer acceptance of BEVs. For this reason, and also because it is expected that the US electricity mix could take longer to decarbonise than the hydrogen mix, the study concludes that FCVs are overall superior to BEVs. For more details of this analysis, also see [15].

Similarly to the MIT study, the validity of the NHA study is also somewhat restricted to the US, due to the specific choice of vehicles, driving cycles and grid electricity carbon intensity assumptions. Moreover, the fact that only one type of vehicle is modelled introduces the same limitations as in the MIT study. Most importantly, the vehicle uptake scenarios considered only allow for one type of powertrain becoming dominant in the long term and hence excluding the possibility of a portfolio of powertrains serving different segments of the private car market.

<u>IEA "Transport, Energy and CO_2 – Moving Towards Sustainability"</u>

The IEA study [1] is much broader in scope than the ones discussed so far, as it addresses the transport sector as a whole and its potential to reduce global GHG emissions in accordance with the targets proposed by the IPCC [6]. The study is self-standing but it also feeds into the broader IEA "Energy Technology Perspectives" study [17]. The analysis is supported by the use of a global transport spreadsheet model called the Mobility Model (MoMo). The model, developed at the IEA, uses both historical data and projections to 2050; it also contains a large amount of techno-economic data for all main types of road vehicles as well as non-road transport modes. In brief, the model calculates costs, energy use and emissions from transport worldwide as a function of a number of variables, which the user can change in order to test the implications of different scenarios.

As for passenger cars in particular, the market penetration of alternative technologies is exogenous, i.e.: penetration scenarios are an input to the model. However, the model is equipped with learning curves, so that the cost of the technologies will change as a result of their uptake. This enables the costs associated with alternative fuels and vehicles to be calculated over time for any scenario modelled. Different types of passenger cars are mentioned in the study, such as sedans, pick-up trucks and SUVs; however results are presented in aggregated form so it is not clear whether they are separately modelled or not. In any case, it seems that average mileage figures are used and different use patterns for different car types are not accounted for.

It is worth mentioning that the IEA Mobility Model also allows testing of modal shifts and passenger travel demand variations. For this purpose, key elasticities are built into the model; in particular, vehicle travel is linked to fuel prices and personal income, and vehicle ownership is also a function of personal income. This makes it easier for the user to build travel demand scenarios that are self-consistent. Finally, the model also tracks materials and resources used for vehicles and fuels production, which effectively enables a lifecycle assessment of the transport technologies considered.

Results of the study suggest that there is potential for cost-effective reduction in fuel use and CO_2 emissions per km from new passenger cars worldwide by as much as 30% in 2020 and 50% in 2030, relative to 2005 levels. This could be achieved by aggressively deploying incremental fuel economy technologies and hybridisation, and would translate into a 50% reduction of fuel use and CO_2 emissions per km from the global stock of passenger cars by 2050. However, if we take into account that a significant growth in global road transport activity is expected, these fuel efficiency gains would only be sufficient to stabilise fuel use and CO_2 emissions from light-duty vehicles worldwide at the level of 2005. To go well below this level it is necessary to also introduce alternative, low-carbon fuels and vehicles, such as, PHEVs, BEVs, FCVs and advanced biofuels. The study suggests that in principle any of these technologies could lead to significant reductions of fuel use and CO_2 emissions on their own, but each one of them also faces barriers. In particular, cost appears to be a significant barrier for all the technologies, at least in the short to medium term. In the long term, however, they could all become cost-competitive but, because projections are uncertain, it is not possible to say which one will be cheaper. However, it is argued that advanced biofuels will also be needed for aviation and shipping and therefore in the long term their availability for use in road transport may be limited. It is also argued that FCVs are a disruptive technology and hence their large-scale adoption faces significantly higher barriers than BEVs, for which a more evolutionary pathway is available via HEVs and PHEVs. Therefore, it is suggested that BEVs are more likely to prevail in the long term than any other technology, and for this reason a scenario where BEVs dominate is explored alongside the BLUE Map scenario where they coexist with FCVs.

The IEA study is clearly more complete and far-reaching that any other study reviewed so far. However, because the whole transport sector is modelled on a global scale, a great deal of detail for the passenger car market in particular cannot be expected. Besides, the model relies on a large amount of input data and assumptions while the results are presented in somewhat aggregated form, which makes the interpretation not entirely straightforward. The study clearly demonstrates that alternative fuels and powertrains are necessary, over and above all possible incremental improvements that can be made to ICE vehicles, if global sustainability goals are to be met. However, it does not provide much analytical evidence on the possible roles of advanced biofuels, FCVs and BEVs respectively in the passenger car sector. In particular, BEVs are hailed as the most likely solution but it is not clear to what extent has the practical feasibility of replacing 90% of ICE vehicles by 2050 with BEVs that have a much shorter range and longer refuelling times been accounted for; arguably, major changes to consumer preferences and driving behaviour would be required

McKinsey/powertrain alliance

The study [10] was carried out by a consortium made of several organisations: 11 car manufacturers, 5 oil & gas companies, 2 utilities, 3 industrial gas companies and other industrial as well as governmental and non-governmental organisations. McKinsey & Company provided analytical support to the study and ensured confidentiality of the data provided by industry. The study builds on results from previous studies, indicating that a) incremental efficiency improvements to passenger cars will be important but not sufficient; b) the potential for replacing oil-derived fuels with sustainable biofuels in passenger cars is uncertain, especially as demand for biofuels in other transport sectors is also likely to be sustained. Therefore, electrified powertrains running on electricity and/or hydrogen will also be needed.

The study compares alternative fuel and powertrain options for passenger cars in Europe by 2050, from an economic, performance and sustainability point of view. The baseline passenger car type is an advanced ICE vehicle with hybrid powertrain, showing a fuel economy that is 30% higher than today's conventional ICEVs. The other vehicle types considered are PHEVs, BEVs, and FCVs. The key characteristic of this study is that, unlike the other studies reviewed so far which mainly use literature data, it relies on a very large amount of up-to-date proprietary industry data. These include vehicle purchase and operating costs, vehicle performance data as well as fuel and infrastructure costs. Another key difference with previous studies is that a balanced mix of passenger car sizes (or segments) is considered, representative of 75% of the passenger car market in Europe; the segments considered are respectively A/B (small cars), C/D (medium cars) and J (SUVs). Other studies usually rely on a single vehicle model, considered as representative of the "average" vehicle type in the region under study.

The study is essentially techno-economic in nature, focuses on the time frame up to 2050 and uses a combination of forecasting and back-casting methods. The analysis is supported by two ad-hoc techno-economic models, one for the vehicles and one for the fuel infrastructures. The two main economic metrics used for the comparison are the purchase price of the vehicle (which includes both actual costs and also profit margins) and the total cost of ownership (TCO), which is the price of the vehicle plus all operating costs (hence also including fuel costs). Moreover, the model also assesses non-monetary indicators such as "overall sustainability" (i.e.: WtW energy efficiency and CO_2 emissions) and performances of the vehicles (such as range, acceleration, refuelling time, etc.). Scenarios are used for possible uptake rates of the different vehicle types in the market segments considered, which take into account their relative strengths and weaknesses. Scenarios are also used for future electricity and hydrogen production mixes. Learning curves are used for technology development projections. Average characteristics of each car segment considered are used to model them, as opposed to specific car models. No vehicle simulation software appears to have been used; instead, average fuel economy values are used. Different distributions of total annual kilometres driven are used for the different segments, which are said to be typically driven over different distances; however, no specific driving patterns are considered.

Having explored various scenarios for alternative powertrain penetration in 2050, it was noticed that the different degrees of penetration of each powertrain type did not dramatically affect their TCO. Therefore it was decided to only investigate in detail a scenario whereby the various powertrain options considered would account for the following shares of the total fleet of passenger cars in Europe in 2050: 25% FCVs, 35% BEVs; 35% PHEVs and 5% ICEVs.

The main finding of the study is that no single powertrain will simultaneously meet all economic, performance and environmental requirements over the next 40 year and beyond; therefore we are likely to move from a single powertrain (ICE) to a portfolio of options, each one playing a different role. In particular, in the long term BEVs and FCVs will be complementary, with the former better suited to smaller cars and shorter trips (commuting and urban driving) and the latter to medium and larger vehicles and longer trips. PHEVs are also an attractive solution for shorter trips and possibly longer trips as well, provided advanced biofuels are available.

The study also finds that initially the TCO of the different vehicle and fuel types considered are quite different; however, the gap tends to reduce over time and is expected to start closing around 2025, or even earlier if incentives are put in place. For larger cars, the TCO of FCVs is expected to be lower than PHEVs and BEVs in 2030 and, by 2050, also significantly lower than ICEVs. For medium-sized cars, the TCOs for all technologies converge by 2050. BEVs have a small TCO advantage over FCVs in the smaller car segments.

Comparison of main findings and limitations of the studies reviewed

Based on the brief review of recent studies discussed so far, it is clear that each of them differs from the others in scope, data used and methods. Therefore, results are not directly comparable and this may pose problems to the non-expert who wants to understand their implications in detail. Despite these differences, though, a high-level story emerges when the studies are considered in chronological order, as we did in our review, and it clearly appears that later studies have been broadly building on the results and methods of earlier ones.

In terms of the results, the studies clearly indicate that incremental improvements to ICE vehicles are very important (MIT, IEA) but will not be sufficient in order to achieve the ultimate policy goals set for road transport (NHA, IEA). They all suggest that plug-in hybrids, biofuels, battery electric vehicles and hydrogen fuel cell vehicles may have a role to play. Moreover, all studies agree that strong policies will be needed in order to achieve mass market adoption of these alternative fuel and powertrain technologies within the expected timeframe. However, there is no general agreement on exactly what the role of each of these technologies should be. It appears that in the long run the use of PHEVs may be constrained by the availability of sustainable biofuels, and that therefore the market may eventually be dominated by BEVs or FCVs (NHA, IEA). As for these two technologies, the dichotomy envisaged by earlier studies is overcome to an extent by the suggestion that each one may successfully serve the needs of different segments of the passenger car markets (McKinsey). This may ultimately result in a lower cost to society than relying on a “one technology fits all” scenario.

As for methods, starting from WtW and LCA studies comparing fuel and vehicle chains on a rather abstract level, later studies have provided increasingly more context to the comparisons by introducing into the equation vehicle uptake and fuel production scenarios, learning curves and more. However, the way in which fuel consumption and emissions per vehicle per km are estimated has largely remained the same as in the WtW studies, i.e.: a single vehicle model is chosen and its use on a standard driving cycle is simulated typically using ADVISOR or similar software packages. This clearly does not provide a good representation of the complexity of the passenger car market, with different segments characterised by different use patterns. Only the McKinsey study explicitly addresses this; however average fuel economy values and total annual kilometres travelled are used, which do not fully reflect the effect of different use patterns of different vehicle segments on their economics and performances. Hence, the detailed characterisation of market segments is an important gap that future studies should seek to address.

Related to this, it is also important to note that, with the exception of the MIT study, the studies reviewed have not explicitly considered changes in car user behaviour. For example, the IEA study considers scenarios where the market is dominated by BEVs, but does not discuss the very significant shift in driving behaviour that these scenarios would entail. Moreover, The McKinsey study bases its assessment of the relative economics of different technologies in key market segments by using today's average annual total kilometres driven, which corresponds to implicitly assuming that driving patters will not change with time and technology. Passenger car adoption and user behaviour, and their possible change as a result of changes in policy and technology, should be further researched and included as appropriate in future comparative studies.

Finally, it is important to note that the studies reviewed don't all compare alternative vehicle technologies in the same way. Different monetary and non-monetary indicators are used across different studies. The most common monetary indicators are vehicle purchase price, which arguably is one of the most important factors influencing adoption of private passenger cars today, and TCO, which is currently not as important for private customers but which could become more important in future. Moreover, the IEA study and to an extent the NHA study also attempt to estimate societal costs of the alternative technologies, where external costs of energy insecurity, GHG and other pollutants are internalised and societal discount rates are applied. Finally, a number of non-monetary indicators are also used, such as performance and overall sustainability, but these are more subjective in nature and hence cannot be compared rigorously across studies. Future studies should also seek to use more consistent indicators and to explain more clearly the implications for policy makers of the different monetary indicators used.

In the remainder of this paper, we attempt to partly address the limitations of the studies reviewed, building on previous work that we have carried out. Based on our findings, we also formulate recommendations for further research and for policy-makers.

Description of analytical framework, data and assumptions

In our previous work the TCO of BEVs and FCVs was compared and the concept of a plug-in-hybrid FCV (FCPHEV) was introduced[18]. We found that FCPHEVs are a potentially very interesting option which has so far largely been overlooked, not least by the comparative studies reviewed.

Then in subsequent work a characterisation of the different market segments in the UK was carried out, using the UK National Travel Survey to generate statistical distributions of daily driving distances for four vehicle sizes ; this was applied to a TCO analysis of BEVs, FCVs and FCPHEVs with variable battery sizes [13, 18].

The characterisation of market segments, more detailed than that of the previous studies reviewed, led to significantly different results compared to using average daily driving distance data across all market segments; hence, the study demonstrated the importance of addressing different market segments in comparative analyses of alternative powertrains. Moreover, TCO analysis of FCPHEVs showed that there are significant diminishing returns with battery sizes above 20 kWh, with an optimum size between 5 and 15 kWh. Because most vehicles are regularly only driven short distances, a larger battery to satisfy occasional long journeys represents a significant stranded asset.

In our previous papers however we did not consider HEVs and PHEVs running on gasoline or bioethanol; hence in this paper the analysis is expanded to include these options. Moreover, we also include the results of vehicle simulations rather than assumed fuel economy values, making our results commensurate with the studies reviewed above.

Figure 2 illustrates all input parameters that must be considered in order to conduct a complete TCO analysis. No study, including this paper, has yet treated all the parameters with the same level of detail. However, unlike previous studies, in this paper all parameters have been clearly identified and those that are not explicitly treated are shown in dashed boxes.

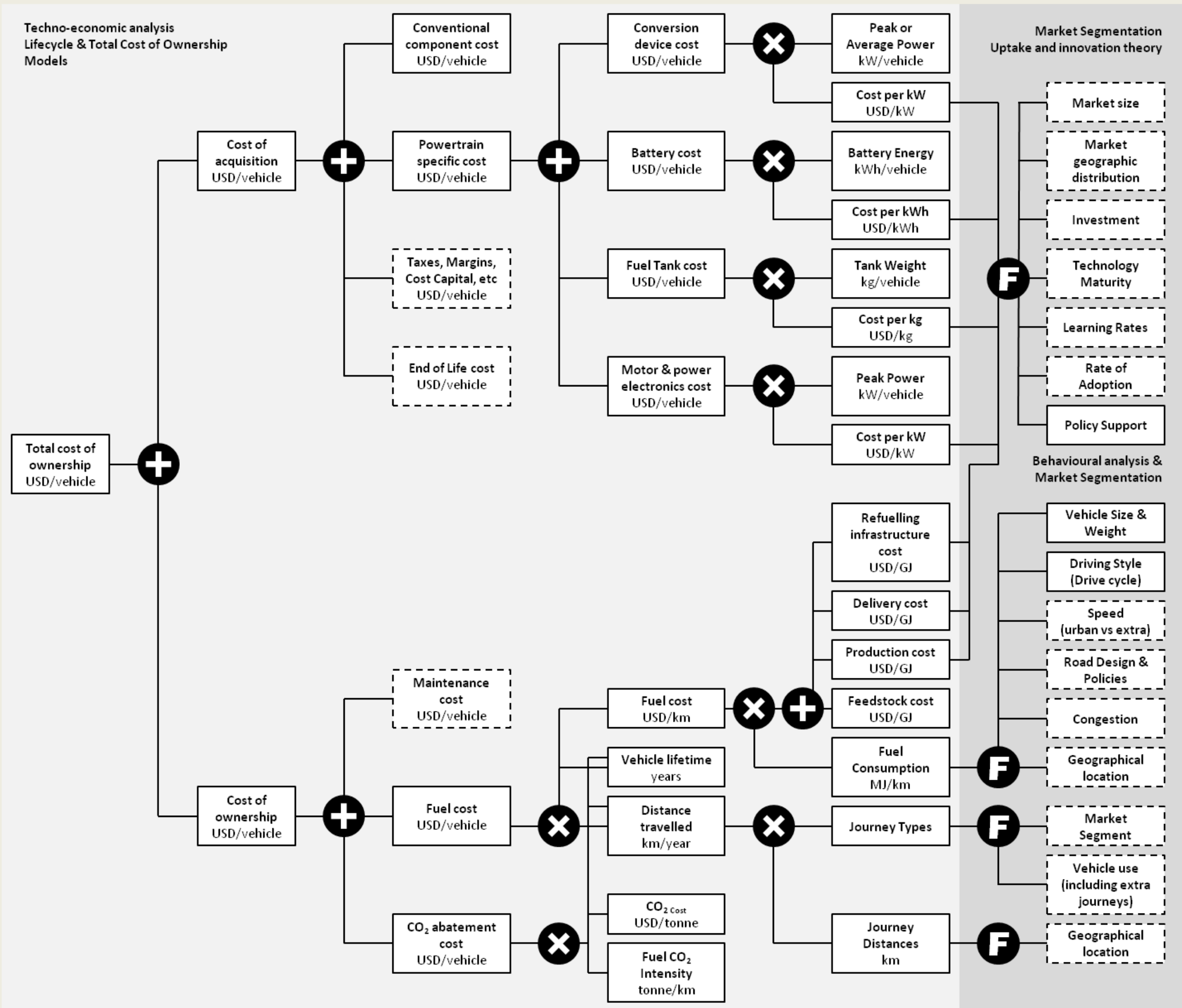

Figure 2. Flowchart illustrating the range of input parameters that must be considered in order to conduct a complete TCO analysis.

TCO model

Much of the methodology and model assumptions are reported in previous papers[13, 18], therefore only modifications or additions to the previously reported model are described here in some detail. Comparisons are made on a tax and profit free basis, and only Well-to-Wheel CO_2 emissions are included. All costs are relative to 2010. Exchange rates of 0.7 GBP equals 1 USD and 1 GBP equals 1 Euro have been used for simplicity when comparing data reported in different sources.

In order to explore vehicle TCO in the future a 2030 scenario is developed. This scenario takes into account the potential for cost reductions in vehicle technologies through technology learning and scale economies as vehicle technologies are deployed commercially. As for the data used in the model, we follow the philosophy of taking as broad a range of values for each variable as makes sense, and then to test the sensitivities and look for tipping points as opposed to using a deterministic approach.

The following sections describe the powertrains types modelled and all main data and assumptions used in the model.

Vehicle platforms

Based upon our previous work four vehicle sizes were analysed corresponding to four market segments: super-mini, lower medium, multipurpose and luxury[18]. Data from the UK National Travel Survey [19] was used to identify driving patterns specific to the market segments.

To give a common basis for comparison, and to ensure compatibility with previous studies, the multipurpose vehicle was also defined as the “typical” vehicle, commensurate with a compact 5-seater saloon type car, such as a VW Golf or Ford Focus. This reference vehicle was assumed to require 80 kW of peak power and 53 kW maximum sustained power; which is commensurate with those used by the JRC [9] and IEA [20] and also similar to the GM Volt. The peak and sustained power assumptions are scaled as appropriate for the other market segments, as described further in section 3.7.

The number of powertrain configurations has been expanded compared to previous work, to include HEVs and PHEVs. ICE HEVs are modelled based upon both parallel and series configurations, and all PHEVs on a series configuration only. A charge depletion followed by charge sustaining energy management strategy was selected for PHEVs, in order to give a fair basis for comparison, as the performance of blended energy management strategies can vary significantly depending on a wide range of control parameters [21]. Furthermore, a charge depletion energy management strategy makes it possible to eliminate tailpipe pollutant emissions for the initial all-electric component of journeys, allowing ICE PHEVs to operate in pollution control areas, such as city centres [22], and offer comparable local air quality benefits relative to BEVs and FCVs.

We also include in our analysis an alternative, downsized PHEV configuration, where a 20kW range extender (be it ICE or FC) is used in the multipurpose vehicle, and scaled as appropriate for the other market segments. While ensuring the same 80kW peak power as the standard powertrain, the downsized powertrain only allows a reduced cruising speed of 70mph. Downsizing has the potential to provide a cheaper vehicle to those customers who are prepared to sacrifice performance. Results of the TCO analysis therefore also include downsized PHEVs, although no further discussion is provided here as we intend to explore this option more thoroughly in future papers.

Hence, a total of eight vehicle platforms have been selected as the minimum necessary to test all the technologies fairly in their most favourable anticipated configuration; they are shown in Figure 3. Battery size is a variable in the PHEV and BEV configurations.

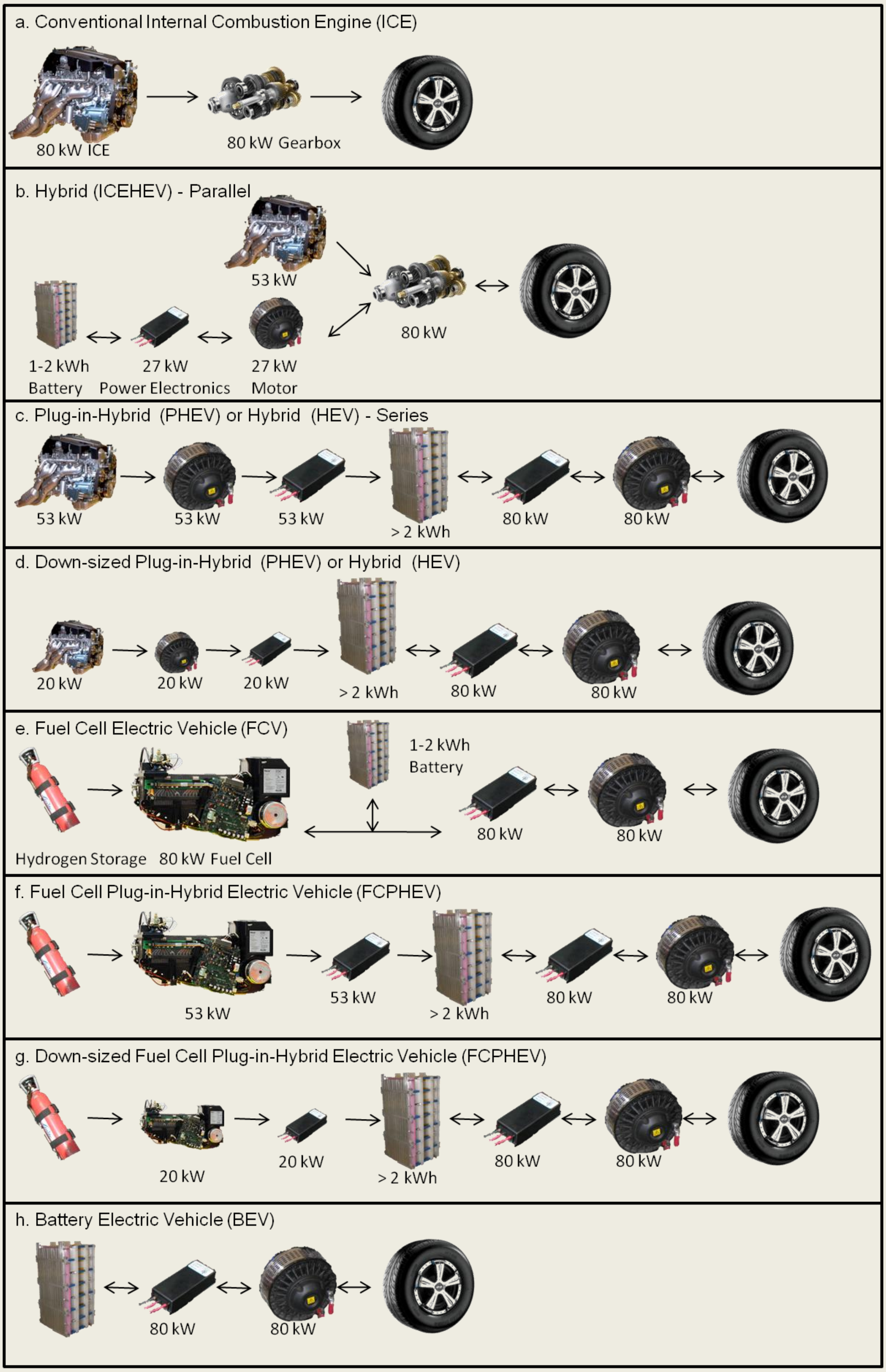

Figure 3. Diagram describing the eight vehicle platforms selected for analysis in the paper; power figures (in kW) are relative to the multipurpose vehicle.

We assumed a base-case vehicle life of 109,000 miles, based upon the weighted average mileage driven in the UK [23] in 2008 of 8,260 miles and the average age of "scrappage" for a UK car in 2007 of 13.2 years[24].

Powertrain and vehicle capital costs

Cost assumptions are summarised in Table 2. State of the art ICE costs have increased in recent years due to the incorporation of new additional engine technologies, such as turbo charging and variable valve actuation and cost around 36 $ kW^{-1} [9], or 50 $ kW^{-1} including transmission [25]. Costs are expected to fall by 2030 due to technology learning; a 5% learning rate applied to newly introduced powertrain/vehicle components would result in a cost reduction by 2030 to 26 $ kW^{-1} excluding mechanical transmission [25]. The mechanical transmission costs are based upon the low (optimistic) and high (pessimistic) costs reported by van Vliet et al. [25]. Therefore the pessimistic cost projections for an ICE engine and mechanical transmission in 2030 is set at current 2010 levels and the optimistic represents a cost reduction of 26%. A fuel tank for gasoline or bio-ethanol costing $125 based upon JRC estimations is included for all liquid-fuelled vehicles [9].

Fuel cell system cost projections are based upon IEA cost targets for 2030 [20] and Li-Ion battery cost assumptions are based upon a review conducted by the British Government in 2008 [26], both assumptions are discussed more fully in our previous work [13, 18]. Improvements were made relative to the previous work regarding the electric powertrain, by including the number, size, and cost of the required electrical machines and power electronics for each powertrain type as shown in Figure 3, rather than a generic assumption representing an 'electric drivetrain'. Optimistic electric motor costs are assumed based upon the generic electric motor in the JRC study [9]. Pessimistic electric motor cost assumptions are based upon the highest costs reported by van Vliet et al. [25]. Pessimistic power electronics costs are assumed based upon the generic motor controller in the JRC study [9] and optimistic power electronics costs are assumed based upon the lowest costs reported by van Vliet et al. [25]. Hydrogen is assumed to be stored as compressed gas with costs based upon the IEA cost target range for 2030 [20].

A single reference vehicle chassis cost of $16,290 was used for the typical vehicle, and additional costs of $300 were imposed on gasoline and ethanol-fuelled vehicles to account for local pollutant control measures, based on JRC cost estimates [9]; these were scaled linearly with peak power demand for different vehicle sizes. Vehicle capital costs were then calculated from the chassis cost plus the powertrain and energy storage costs for all vehicles.

Table 2. 2030 vehicle powertrain capital cost assumptions

Component	2030 Optimistic	2030 Central	2030 Pessimistic
Internal combustion engine	$26 kW^{-1}	$28.5 kW^{-1}	$31 kW^{-1}
Mechanical Transmission	$11 kW^{-1}	$15 kW^{-1}	$19 kW^{-1}
Fuel cell system	$35 kW^{-1}	$55 kW^{-1}	$75 kW^{-1}
Battery system	$200 kWh^{-1}	$250 kWh^{-1}	$300 kWh^{-1}
Electric motor	$8 kW^{-1}	$12.5 kW^{-1}	$17 kW^{-1}
Power electronics	$6 kW^{-1}	$12.5 kW^{-1}	$19 kW^{-1}
Pollution control gasoline	$300	$300	$300
Fuel tank	$125	$125	$125
Compressed H_2 tank	$900	$1,450	$2,000

Technology-specific assumptions

Li-Ion batteries are assumed to be capable of deep discharging to 20% State of Charge (SOC). Li-Ion batteries are therefore oversized by 20% to ensure that the *all-electric range* (AER) is met. A minimum Li-Ion battery capacity of 1.3 kWh is also assumed for the typical vehicle which does not form part of the AER capacity so as to provide sufficient power reserves for strong acceleration in emergency events and for hill climbing.

Due to the high costs of both PEMFCs and batteries it is critical that these powertrain components have a calendar life equal or greater than the lifetime of the vehicle, as replacing them will not be economically feasible [21]. The durability of PEMFCs and state-of-the-art Li-ion battery chemistries has not yet been fully determined under real-world driving conditions. However, experimental results from recent studies indicate that current PEMFCs will meet DOE/FreedomCAR durability targets of 150,000 miles [27]. Similarly, experimental results on state-of-the-art Li-ion battery chemistries indicate calendar lives of over 12 years and a cycle lives of thousands of deep discharge cycles [28]. Furthermore, it is expected that the calendar life and durability of state-of-the-art fuel cell and Li-ion batteries will increase significantly over the coming decade. Electric motors are expected to have a lifetime of over 6,000 hours [25] as they have few moving parts and should not face considerable heat stresses if the system is well designed.

As a result, all powertrain components, including PEMFCs and batteries, are assumed to have a lifetime greater than of the vehicle lifetime in 2030.

Fuel cost and availability

In order to determine the TCO of alternative vehicle options it is necessary to consider the vehicle running cost in addition to the vehicle capital cost. Fuel cost assumptions are summarised in Table 3. The assumptions for gasoline, hydrogen and electricity are described in detail in a previous paper [13]. The rationale for our future cost of ethanol assumptions are outlined below.

Table 3: Fuel cost assumptions

Fuel	2030 Optimistic ($ GJ^{-1})	2030 Central ($ GJ^{-1})	2030 Pessimistic ($ GJ^{-1})
Gasoline	19.0	28.5	38.0
Hydrogen	14.0	35.0	56.0
Electricity	26.9	35.8	44.7
Bioethanol	20.0	30.0	40.0

Whereas electricity and hydrogen can be produced from all types of renewable energy, renewable ethanol is currently only produced easily from biomass. In 2010, global ethanol production was estimated to be 85.6 billion litres, the vast majority of which (>95%) was produced by fermentation of sugar and starch [29]. The ~5% of ethanol that was not derived from biomass was produced from fossil fuels via the catalytic hydration of ethylene [30].

Sugar and starch, however, are commodity food crops and their conversion into transport fuel has become increasingly controversial. Production of ethanol from maize, in particular, has been blamed for rapid food price inflation and causing a direct and indirect negative impacts (for example land use change and deforestation) [31] [32] [33]. The development of the EU mandate for renewable transport fuels – that 10% of the final consumption of energy in transport should come from renewable sources by 2020 [34] – was influenced by these sustainability concerns. The final version stipulated minimum GHG saving thresholds[a] and placed restrictions

[a] 35% rising to 50% from 2017 and 60% from 2018

on producing biofuels on forested and bio-diverse land. These constraints are expected to limit the use of conventional feedstocks and drive the development of technologies that can produce ethanol from lignocellulosic biomass[b] [35]. Compared to conventional feedstocks, lignocellulosic biomass is more abundant, holds the promise of attractive GHG savings and more limited conflict with land use for food and feed production [36] Lignocellulosic ethanol is the subject of major research efforts in the EU and USA and it is plausible that it could be fully commercial by 2030.

Our 2030 scenario for biofuels assumes that ethanol will be produced from lignocellulosic biomass. Numerous estimates of future costs have been undertaken, as shown in Table 4. Estimates for the future production cost of ethanol from conventional sources are also shown for comparison. Our optimistic estimate is \$20 GJ^{-1}. This value approximates to ethanol produced from agricultural residues in large fully commercial facilities. Our central value is \$30 GJ^{-1}. This corresponds to production from more expensive wood feedstocks in a smaller facility, or a slightly more cautious view of production from agricultural residues. Our pessimistic estimate is ~\$40 GJ^{-1} which corresponds to fully commercial, but relatively small scale production, from more expensive feedstocks. For comparison purposes the price of gasoline at the pump on a tax free basis in 2005 (a similar time period to when the ethanol studies were published) was 19.8-22.6 \$$GJ^{-1}$ [37].

Table 4: Estimated future ethanol production costs from lignocellulose and conventional feedstocks

Reference	**Conversion process** [a]	**Capacity** [b] **(tonnes dry biomass.year^{-1})**	**Ethanol production cost. 2010\$.GJ^{-1}(HHV)**
Conventional feedstock's			
RSC 2008 [c 38]	Conventional fermentation	Sugar cane	12-17
		Corn	17-26
		Sugar beet	19-28
		Wheat	21-31
Lignocellulosic feedstock's			
Von Sivers and Zacchi [39]	Enz. / dilute acid / conc.acid	100 000 (S)	38/41/40
Lynd [40]	Enz.(SSF)	592 000 (H)	20
NREL [41-43]	Enz.(SSF)	700 000 (H)/(CS)	24/17
Wingren [44]	Enz.(SHF) / Enz. (SSF)	196 000 (S)	40/32-34
Sassner [45]	Enz. (SSF)	200 000 (H)/(CS)/(S)	36/36/29

[a] Process classified according to the principle hydrolysis step: Enz. = enzymatic hydrolysis; SSF = simultaneous saccharification and fermentation; SHF = separate hydrolysis and fermentation.
[b] S = softwood; CS = corn stover; H = hardwood
[c] projected cost of production in 2030

Source: adapted from [46] [38] [47] [29]

CO_2 emissions and the cost of carbon

In order to assess the CO_2 emissions of all vehicle/fuel options it is necessary to consider the whole fuel cycle from well to wheel (WtW).

- WtW gasoline CO_2 emissions are taken as 85.9 gCO_2/MJ^{-1} [9].

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[b] Lignocellulosic biomass includes wood and forestry residues, agricultural residues – e.g. wheat straw, maize stalks and cobs (corn stover) – and purpose grown energy crops such as short rotation coppice, miscanthus, switch grass, etc.

- We assume a range of scenarios whereby electricity in 2030 is 80%, 50% and 20% decarbonised respectively. As a result, 2030 electricity CO_2 content is assumed to be 120, 75 and 30 gCO_2/MJ^{-1} for pessimistic, central and optimistic scenarios respectively [13].
- Hydrogen CO_2 content is taken to be 98.2 gCO_2/MJ^{-1} [9], based upon the assumption that hydrogen will still be predominantly produced by steam methane reforming in 2030.
- Ethanol CO_2 content ranges between 12.5 gCO_2/MJ^{-1} based upon lignocellulosic ethanol from wheat straw, with lignin used for process heat and electricity generation, to 59.5 gCO_2/MJ^{-1} based upon ethanol from sugar beet, with pulp used for DGGS (animal feed) [48]. We assume an average of 36 gCO_2/MJ^{-1} for the central scenario.
- The cost of CO_2 is highly subjective. In the report published by the US Energy Information Administration in response to a question about the American Clean Energy and Security Act of 2009 it was estimated that the price of carbon could be between $41 and $191 by 2030. Therefore a central assumption of $116 per Tonne of CO_2 in 2030 was used with a range between $41 and $191.

Factoring the cost of WtW CO_2 emissions into our TCO analysis corresponds to assuming that these costs will be internalised and passed on to end users by 2030. Similarly, one could assume that the CO_2 emitted throughout the whole lifecycle of the vehicle and fuel, including manufacturing and disposal processes, would also be internalised eventually. In this study however, unlike the MIT, IEA and McKinsey studies, we did not perform an LCA. LCA of alternative powertrains and fuels is a rapidly evolving field and this, together with its data-intensive nature, explains why we restricted our analysis to WtW CO_2 emissions. However, results of the MIT study suggest that, for all powertrains and fuels considered in our analysis, production and disposal processes are responsible for an additional 20-30 g(CO_2 equiv)/km.

Vehicle energy consumption

In order to ensure a realistic outcome for the running costs and WtW CO_2 emissions of each powertrain type, it is necessary to examine the energy consumption per mile of the vehicle. For this purpose, two different vehicle simulation tools, AVL Advisor (Advisor) and AVL Cruise (Cruise), have been used. In our simulations we use a driving cycle which was developed as part of the European research project ARTEMIS and represents the characteristics of European driving conditions and behaviour more accurately than the NEDC [49].

In order to assure a correct comparison between the various powertrains a baseline vehicle platform is adopted. The characteristics of the reference vehicle platform are summarised in table 5.

Table 5. Characteristics of the reference vehicle platform

Curb weight / kg	1400.00
Wheel base / mm	2810.00
Drag coefficient	0.27
Frontal area / m^2	2.20
Rolling resistance coefficient	0.012
Static rolling radius / mm	300.00
Dynamic rolling radius / mm	317.00
Additional load / kg	115.00

Electric powertrains were modelled with the ability to partly recover the energy otherwise dissipated during braking. These powertrains are the HEV, BEV, FCV and all PHEV configurations, i.e.: all those equipped with a battery and an electric motor. This leads to a reduction of the energy consumption of approximately 1.5-3.5%.

The design of a PHEV presents a particular challenge because the PHEV is propelled by both electricity and a chemical fuel. PHEVs are typically characterised by a PHEVx notation, where the "x" denotes the AER (which in this paper is expressed in miles). The AER is a function of the maximum energy storage capacity of the battery. For example, a PHEV50 can nominally drive for 50 miles on electricity alone before needing to operate its range extender, although the notation is somewhat ambiguous as it depends upon the definer's choice of driving cycle. As described above a charge depletion followed by charge sustaining energy management strategy was selected for PHEVs, therefore the analysis was divided into two parts.

In order to take into account improvements in ICE powertrains by 2030, such as direct injection, variable valve actuation and stop-start, we introduced an improvement factor of 0.2 to the energy consumption of the ICEVs and HEVs. Table 6 summarises the simulated and estimated energy consumptions of the various powertrains.

Table 6. Summary of the energy consumptions for the various powertrains

Vehicle Energy Consumption / MJ mile^{-1}				
Powertrain type and mode of operation	Super-mini	Lower medium	Multipurpose	Luxury
ICEV	2.15	2.46	2.74	3.91
HEV Parallel	1.92	2.19	2.45	3.49
HEV or PHEV, Charge Sustaining	1.69	1.93	2.15	3.07
PHEV, Charge Depletion	0.99	1.13	1.26	1.80
FCV	1.54	1.76	1.96	2.80
FCPHEV, Charge Sustaining	1.30	1.49	1.66	2.37
FCPHEV, Charge Depletion	0.99	1.13	1.26	1.80
BEV	0.75	0.86	0.96	1.37

Driving behaviour

Driving behaviour is an important input to a TCO analysis. Firstly, the driving cycle, be it urban, extra-urban or mixed, has a significant impact on the vehicle's energy consumption per mile. Another important factor is driving style, i.e. the pattern of acceleration and deceleration that can be associated with a particular driver; this is also known to have a large impact on energy consumption. For example, in a recent study of low-carbon vehicles in the United Kingdom [50], large differences in energy consumption up to a factor of 2 were reported for the same vehicle being driven by different drivers around a defined test track; this was mostly associated with braking choices.

Moreover driving patterns (i.e.: lengths of individual trips and total distances driven per day) are particularly important for the TCO of any PHEV powertrain configuration; in fact, for a given battery size, it is driving patterns that determine the utility factor, i.e.: the percentage of total miles driven on electricity only over the lifetime of the vehicle[51, 52].

When conducting a TCO analysis, therefore, one approach is to ignore these differences across market segments and use a statistically averaged driving behaviour. This approach was largely taken in the studies reviewed in Section 2 as well as in previous papers by the authors [13, 18]. A degree of market segmentation was also explored in one of these previous papers[13], where differences between driving patterns associated to main vehicle segments were found. In particular, we found that small cars are generally driven over significantly shorter daily distances than larger cars. This suggests that a certain degree of specialisation is already present in today's car market, although the nature of ICE powertrains makes these cars good "all-rounders", capable of relatively high performances and long ranges regardless of the size. It can be argued however that the transition towards alternative fuels and powertrains will be accompanied by an increased specialisation, where different powertrain and fuel options will satisfy the needs of different market segments. For example BEVs may become dominant as small cars used for urban mobility, whereas PHEVs and FCVs may be more suitable for larger cars used over longer distances [10]. If this happens, today's driving patterns will arguably also change, as drivers' behaviour adapts to using more specialised vehicles.

In this paper we initially use the same statistically averaged driving behaviour generated from the UK National Travel Survey which is described in detail in the previous paper [13]; however later in the results we explore the significance of taking market segmentation and behavioural changes into account in future TCO studies.

Results & discussion

General results

Results of the TCO analysis are presented as follows, with the first number representing the nominal power of the ICE or FC (as in 80ICE which is an 80kW ICEV or 80FCV which is an 80kW FCV) and the second number being the AER of the vehicle in miles (as in 53PHEV25S or 53FCPHEV25, which is a PHEV with a 53kW ICEV or 53kW FCV respectively, with 25 mile AER). For an ICEV the S or P denote Series of Parallel configuration, a FCV is always in series configuration, and for an ICEV the Bio denotes the use of bioethanol instead of petrol. Results for the typical vehicle, based upon the central assumptions, average driving pattern and a 25 mile (40 kilometre) AER for PHEVs, are shown in Figure 4.

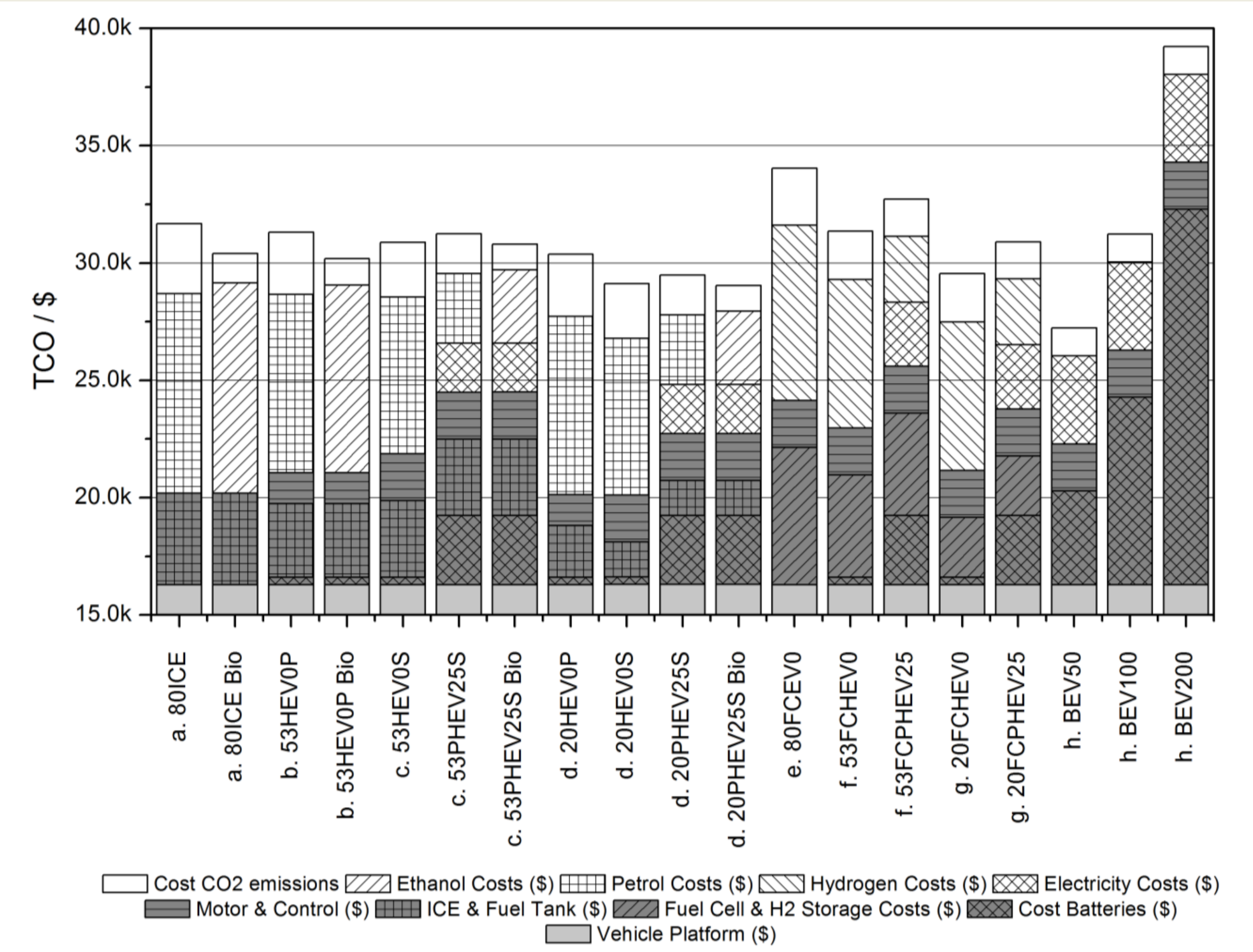

Figure 4: Results of the TCO analysis using the central assumptions for the typical vehicle, with 19 possible powertrain configurations; all PHEVs have a 25 mile (40 kilometre) AER.

It can be seen that TCOs of all vehicle and fuel configurations are broadly similar, except for BEVs where the cost of the battery becomes dominant as its size increases. Figure 5 shows the results where the optimistic, central and pessimistic assumptions are presented for selected powertrains; it appears that any differences are within the sensitivity ranges of the assumptions. This result is consistent with the findings of the IEA and McKinsey studies [1, 10].

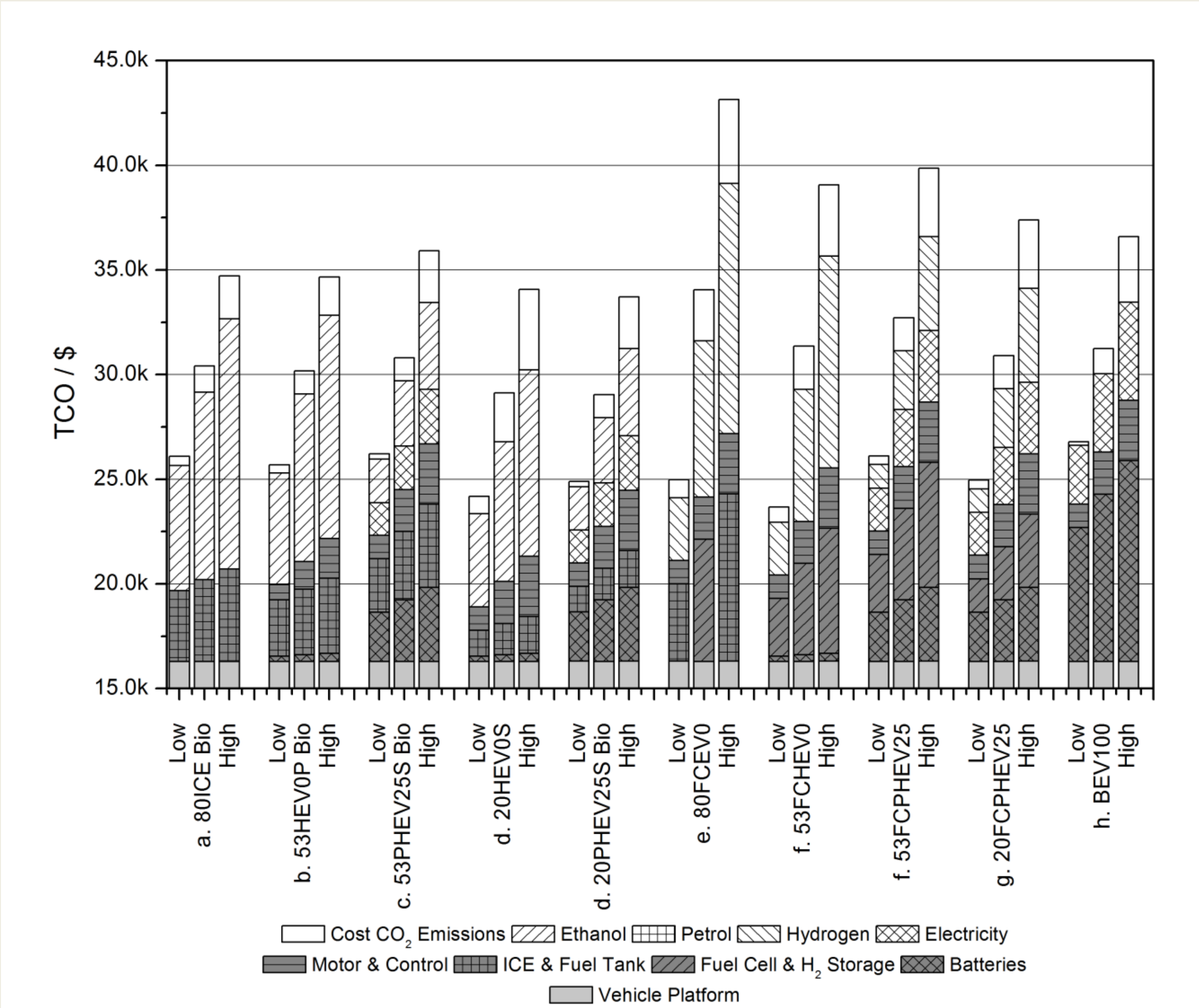

Figure 5: Sensitivity analysis showing the optimistic, central, and pessimistic assumptions for the typical vehicle, for 10 selected power train configurations, all PHEVs have a 25 mile (40 kilometre) AER.

The choice of driving cycles in a TCO analysis using vehicle simulation tools will affect the energy consumption per mile and therefore fuel cost for all powertrains. The most appropriate driving cycle to use will be a function of many factors, as shown in Figure 2, such as vehicle size, type of driving (i.e. urban vs. extra-urban), driving style, road design, speed limits and congestion. The effect of these factors is expected to be significant, with the difference caused by driving style alone shown to affect the energy consumption by up to a factor of 2 [50]. Here we test the sensitivity of the result of the TCO analysis to different driving cycles by reproducing the results above, using the central assumptions, but varying the energy consumption by +/-33%, as shown in figure 6. For all PHEVs the battery size has been kept the same, therefore the AER will vary proportionally to the energy consumption per mile; however, for the BEV the battery size is changed in order to show the cost of guaranteeing a specific AER.

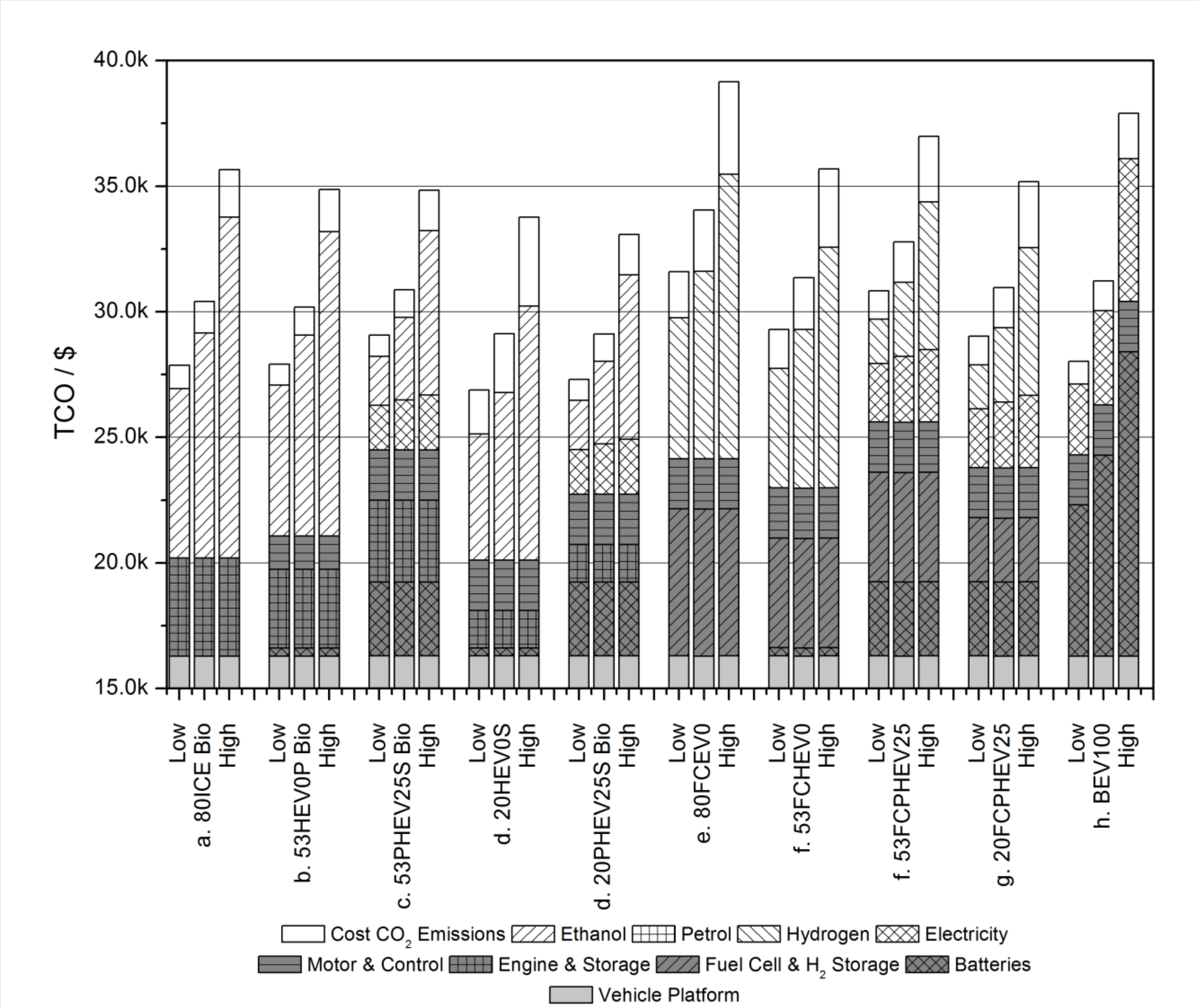

Figure 6: Sensitivity analysis showing the effect of varying energy consumption by a factor of 2. Central assumptions for the typical vehicle. All PHEVs have a fixed battery size and therefore variable AER.

The effect of varying the energy consumption by a factor of two introduces almost as much uncertainty for most powertrains as the effect of all the other assumptions put together, except for fuel cell vehicles where the range of fuel cell cost assumptions is very large. However, perhaps surprisingly, it changes the TCO results relatively uniformly and therefore does not change the overall trend. Despite this, there are important implications for both PHEVs and BEVs that are worth discussing briefly. The actual AER of the PHEV25s is significantly affected by the choice of driving cycle; in our test it varies from roughly 15 miles to roughly 35 miles; the resulting utility factor ranges between 39% and 69% respectively, and this has significant consequences on both fuel consumption and CO_2 emissions. Hence we can infer that uncertainty around the environmental and energy security performance of PHEVs due to the effect of driving cycles is great. Because this source of uncertainty has generally not been accounted for in previous TCO studies, their results should be interpreted critically. As for BEVs, it is the range of the vehicle that varies as a function of the driving cycle. In order to guarantee a minimum of 100 miles AER over any driving cycle, the cost of the BEV100 increases very significantly solely as a result of the requirement for a far larger battery pack. It follows that BEVs should preferably be designed and marketed as vehicles for low-energy driving cycles, such as urban and slow extra-urban.

Market segmentation

In previous work it was demonstrated how important the combination of driving patterns and battery size is to the result of a TCO analysis that includes PHEVs [13]; this is not reflected in the results above where an arbitrary 25 mile (40 kilometre) AER is selected.

As discussed above, we argue that market segmentation is key to future improvements to TCO studies, and as such we have used the approach from our previous work [13]. Data from the UK National Travel Survey [19] are used to identify driving patterns for four market segments: super-mini, lower medium, multipurpose and luxury. As figure 7 shows, the distribution of daily driving distances in the UK varies significantly across these market segments. In particular, smaller vehicles are generally driven over shorter distances than larger vehicles.

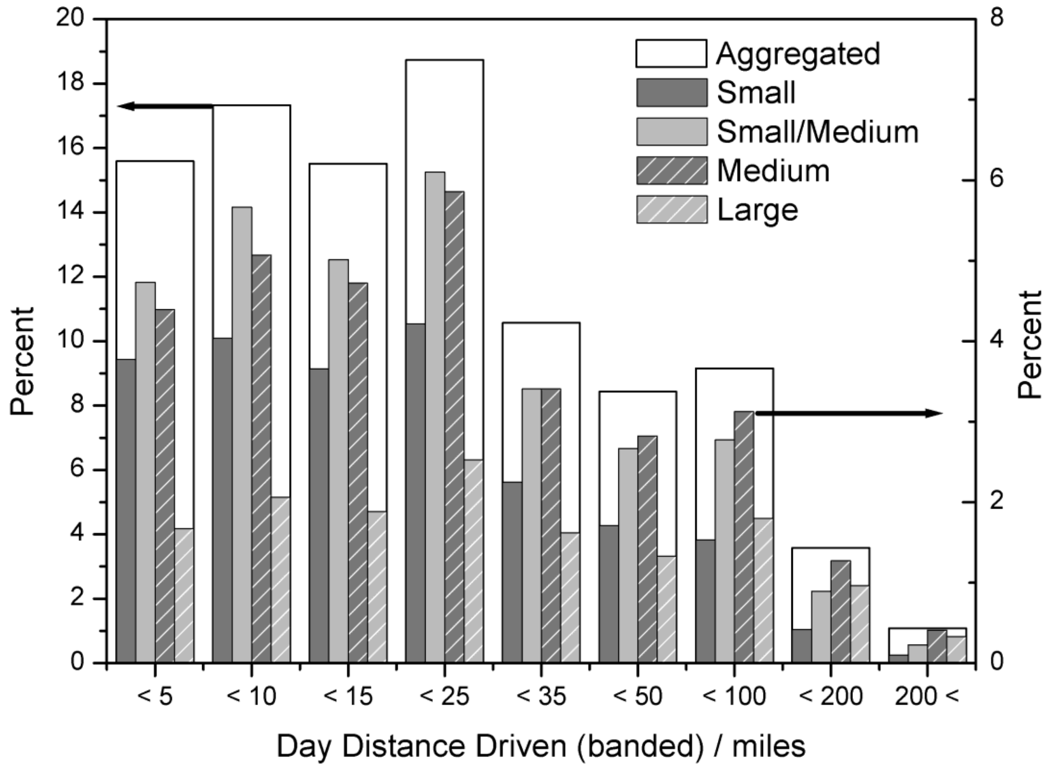

Figure 7: Data extracted from the UK National Travel Survey, showing the aggregated average daily distance travelled by private car in white with the axis on the left, and the breakdown of average daily distance by car types shown in various labelled shades of grey with the axis on the right. Source: [13]

If we now consider the driving patterns of figure 7 and we examine the TCO of BEVs and PHEVs as a function of battery size for each of the segments considered, we can demonstrate analytically that BEVs are better suited to smaller vehicle segments whereas PHEVs and FCVs are better suited to larger vehicle segments. Figure 8 shows the results of the TCO analysis for the two extreme cases: the super-mini (a) and the luxury (b) segments; the results for the two intermediate segments obviously fall in between the two extremes.

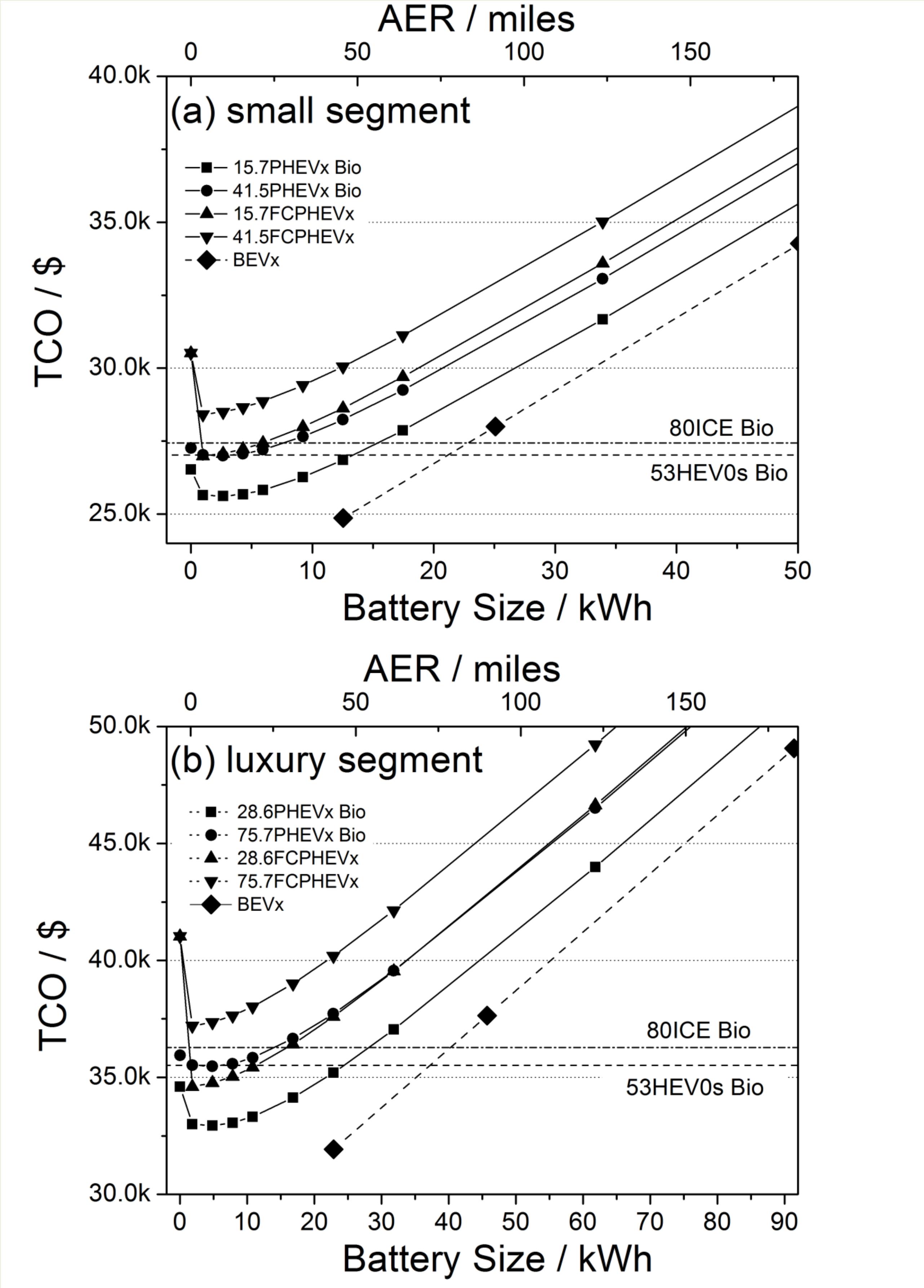

Figure 8: Results of the TCO analysis for PHEV and BEV powertrains for 2 market segments: (a) super-mini and (b) luxury, with variable battery sizes.

Moreover, the same effect seen in previous work [13] for the FCPHEV is shown for all of the PHEV powertrains. The costs of ICE PHEVs are slightly lower than FCPHEV due to the higher capital costs of the fuel cell compared to the ICE based upon the central assumptions, but otherwise the results are very similar. Diminishing economic returns are observed for all vehicle segments for battery sizes above 20 kWh, with the optimum size for a PHEV battery falling between 5-15 kWh. However, for similar battery sizes, the AER and hence the utility factor will be noticeably reduced for larger vehicles; this has a significant impact upon fuel consumption and emissions. Note that the cost difference between the petrol and bioethanol fuelled vehicles is negligible considering that the cost assumptions are very similar therefore only the bioethanol version is presented in figure 8.

Behavioural change

As mentioned above, it can be argued that the uptake of alternative powertrains will influence behaviour and therefore the driving patterns observed today will no longer apply in future.

For example, if we accept that BEVs with limited range will eventually take up a significant share of the super-mini vehicle market segment, then these vehicles are likely to no longer be used for the occasional long journey they currently do according to the distribution shown in figure 7. These journeys will therefore probably be carried out using vehicles from other segments of the market where PHEVs and FCVs are competitive. More generally, we can expect that, due to the introduction of more specialised vehicles, the differences in daily driving distances across market segments will become more pronounced. However, the coarsely resolved market segmentation we have presented here is probably not sufficient to explore this effect in detail. Hence, a more refined segmentation of the market should be carried out in future studies in order to better explore possible shifts in driving patterns and their effects on TCO analysis.

Moreover new business models, such as vehicle rental by the hour and car clubs, if adopted on a large scale have the potential to change the results of the analysis even more drastically. These business models decouple drivers from vehicles, thus potentially allowing the driver to select the most appropriate vehicle for each journey. So even if car users' driving patterns remained the same as today, the TCO calculation would be based on the driving pattern of the vehicle and not of the individual user, and results would significantly differ from those presented in this paper. Moreover, the other likely effect of these new business models would be to increase the utilisation of the vehicle (i.e.: the total number of miles driven over its lifetime), which again would influence the results of the TCO analysis. Figure 9 below shows the sensitivity of the TCO of the multipurpose vehicle to its utilisation, under baseline assumptions. It is evident that, *ceteris paribus*, the relative TCO of the various powertrains changes quite significantly with utilisation; in particular, BEVs move from one of the most expensive to one of the cheapest options as utilisation increases. More generally, vehicles with high capital costs and lower running costs benefit from higher utilisation; hence, their economics would both favour and be favoured by establishing new business models such as those mentioned above. Vehicles with lower capital costs and higher running costs, however, would not be incompatible with the new business models either, thanks to the diversity that characterises the passenger car market.

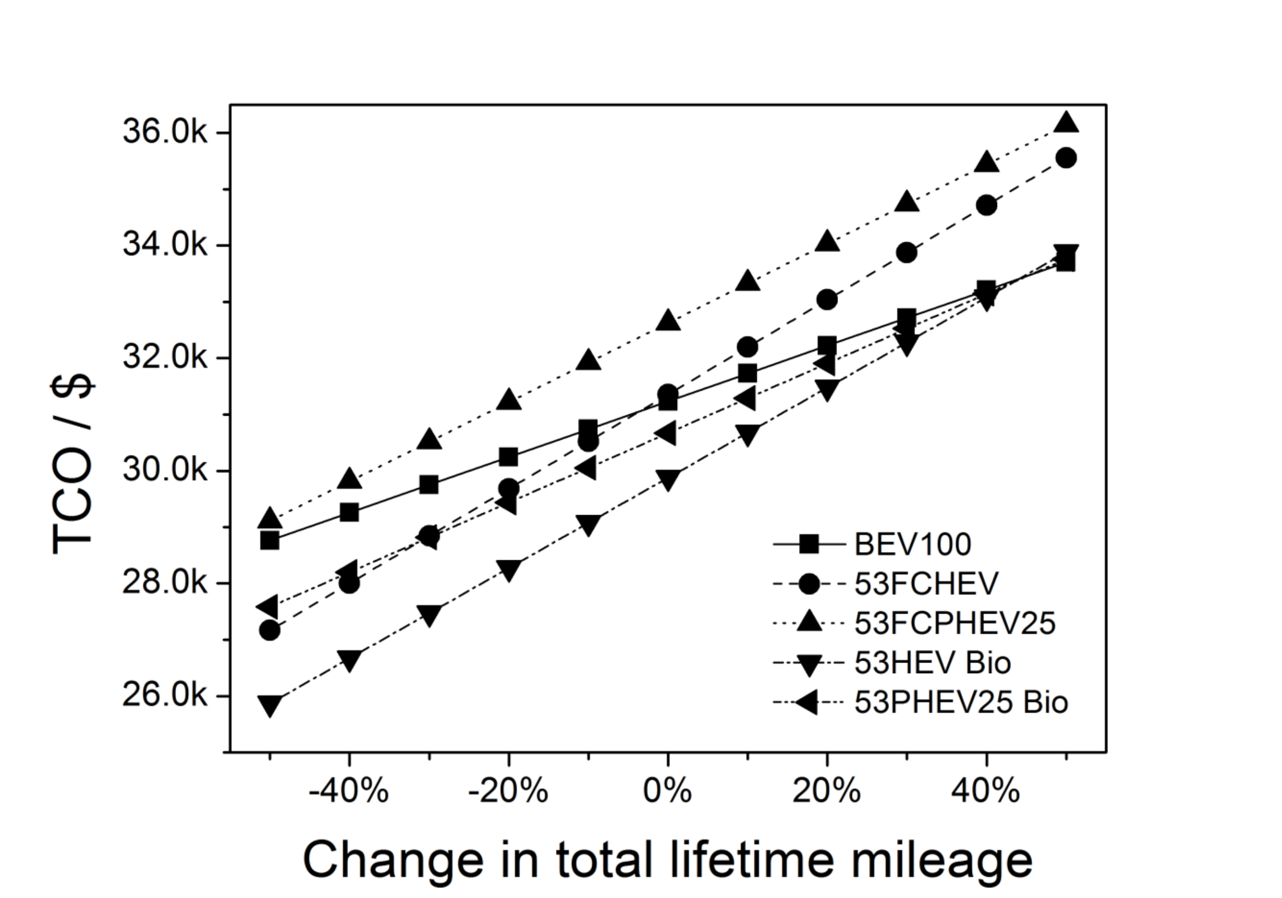

Figure 9: Sensitivity of the TCO of selected powertrains to the utilisation of the vehicle (i.e.: the total miles driven over its lifetime). The figure shows results for the multipurpose vehicle segment under baseline assumptions.

Different indicators and interpretation of results

In Section 2.3 we have already mentioned that the studies reviewed don't all compare alternative fuel and powertrain options using the same indicators, and that it would be desirable if future studies used consistent methods and indicators in order to be more easily compared. However, the results of our TCO analysis suggest that this would not necessarily be sufficient in order to guarantee comparability and ease of interpretation of future studies. In fact previous TCO analyses mainly address uncertainty in terms of cost and technical performance of fuels and powertrains, but do not account for behavioural change. When the latter is also built into a comparative analysis, uncertainty becomes much larger than the previous studies reviewed suggest, the more so longer the time horizon of the analysis. Hence, for the results of the studies to be easy to interpret and compare, all key assumptions and uncertainties need to be clearly and transparently discussed.

Another important implication of uncertainty is that studies focusing on a short time horizon, for which technology projections are relatively straightforward and today's behaviour largely valid, can be conducted in a deterministic manner and their results can be seen as relatively reliable from a quantitative point of view. However, studies focusing on longer time horizons, regardless of the indicator used, are affected by so much uncertainty that their results should be considered as explorative rather than predictive. In other words, given the impossibility to anticipate future developments with any certainty, the studies would instead aim to explore different scenarios and understand their potential implications. In this context, not only technology development scenarios but also behavioural changes should be explored, in order to capture the full spectrum of possible future developments.

Conclusions and recommendations

In this paper we have selected and reviewed seven high-profile studies comparing hybrid, plug-in hybrid, battery electric and hydrogen fuel cell vehicles, and biofuels. Although the studies differ in terms of scope, data used and methods and hence their results are not strictly comparable, a coherent high-level story clearly emerges if they are considered in chronological order. In particular, the studies suggest that incremental improvements to ICE vehicles have an important role to play in the short to medium term; however, in order to meet long-term policy targets, alternative fuels and powertrains will be necessary and strong policies will be required to promote their rapid development and uptake. Moreover, in the long run PHEVs may be constrained by the availability of sustainable biofuels, hence both BEVs and FCVs are expected to play an important role. In particular, the latter technologies are seen as largely antagonistic and mutually exclusive in earlier studies, while more recent studies argue that both BEVs and FCVs are needed as they will be serving different segments of the passenger car market.

Our review of previous studies also suggests that, despite having generated and synthesised a tremendous amount of knowledge, they show some limitations which future studies should seek to address. In particular: a) the complexity of the passenger car market, consisting of many segments characterised by different requirements and use patterns, is not adequately represented; b) future changes in driving behaviour brought about by new policy and technology are generally not considered; c) different studies use different indicators to compare alternative fuels and powertrains, making results difficult to compare and their interpretation difficult for the non-expert.

In the remainder of the paper, we have sought to further explore the limitations of the studies reviewed by performing a TCO analysis which builds on previous work by the authors. In particular we have shown that, comparing alternative fuels and powertrains based on a single vehicle platform and using average driving patterns, the costs of all options are close and within the error margin. In other words, nothing can be said as to which one of them would be the least-cost option. This result is in line with the findings of the most recent studies reviewed. However, building different vehicle segments and driving patterns into our TCO analysis, we found that costs start to diverge and that certain fuel and powertrain options are more competitive than others for given market segments. This shows the importance of taking into account the diversity of the passenger car market in future comparative studies. Moreover we also demonstrated that taking into account possible future changes in driving behaviour can also alter the results of a comparative study quite significantly. So far, these studies have largely been based on today's driving patters and this is acceptable if the time horizon of the comparison is near, but almost certainly unacceptable if the comparison is projected into a more or less distant future. So, we suggest that behavioural change should be accounted for in future comparative studies. Finally, we also suggest that not only more uniform indicators and metrics should be used in future comparative studies, be they WtW, TCO or societal cost analyses, but that crucially the high uncertainty and hence explorative (as opposed to predictive) nature of the long-term studies should always be made clear, for the benefit of the non-experts.

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