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Current Hybrid-Electric Powertrain Technologies: Evaluation of Architecture Designs and Empirical Analysis of Whole-life Costing

Tim Hutchinson[a,b,*], Stuart Burgess[c], Guido Herrmann[c]

[a] *Industrial Doctorate Centre in Systems, University of Bristol, Bristol, BS8 1UB, UK*
[b] *Triumph Designs Limited, Hinckley, LE10 3BZ, UK*
[c] *Department of Mechanical Engineering, University of Bristol, Bristol, BS8 1TR, UK*

Abstract

The recent introduction of hybrid-electric powertrain technology has disrupted the automotive industry, causing significant powertrain design divergence. As the radical powertrain innovation matures, it is inevitable that the industry will converge once more and that dominant designs will emerge, but which designs will endure? With over 50 hybrid models now available in the US including a range of distinct architectures, the capabilities of hybrid powertrains are now becoming clear and undergoing real-life testing. This study seeks to take advantage of the position that the industry has reached, replacing previous theoretical models with an empirical view of hybrid powertrain technologies. A comprehensive snapshot of today's hybrid market is presented, with detailed descriptions of the various hybrid powertrain architectures that exist. Empirical analysis is performed to understand their relative economic competitiveness and predict the emergence of potential dominant designs. It is found that the value to be seen in hybrid powertrains is strongly dependant on the vehicle's application, in terms of both market conditions and manner of use.

Keywords: Mild hybrid, Full hybrid, Plug-in hybrid, Series hybrid, Powertrain comparison, Whole-life costing

1. Introduction

The global depletion of natural resources and emission of harmful gases have seen much attention in recent years as environmental issues become increasingly recognised in global agendas. The transport industry has been identified as a significant problem area, due to its heavy reliance on traditional internal combustion engines (ICEs) for power. Whilst customers are increasingly seeking greener products and services, regulators are also creating ever stricter legislation and this is driving real change in the automotive industry.

Since the release of the original Toyota Prius in 1997, the development of new alternative powertrain passenger vehicles has risen almost exponentially, with the majority of global manufacturers having released hybrid-electric models. Fig. 1 displays the trend in the number of hybrid-electric passenger car models on sale from the world's fourteen largest car manufacturers over the last fifteen years. This trend has led to an ever increasing number of hybrid cars in high street showrooms, with the current count at over 50, allowing the technology to reach broader customer groups and diffuse deeper into the market. A similar trend can also be seen in Fig. 1 for hybrid car sales, although they still make up only a small share of the US and European passenger car markets, at 3.2% and 0.7% respectively [1, 2, 3]. Whilst the world's fourteen largest passenger car manufacturers are all producing hybrid vehicles, there are several that appear to be leading the way. In particular, Toyota has retained its market lead since the 1997 Prius, with its sales accounting for almost 70% of hybrid passenger car sales in the US in 2012 [4], as seen in Fig. 2.

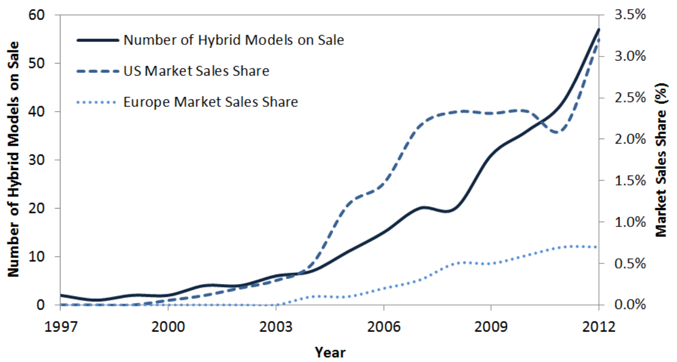


Fig. 1. Historical Hybrid Market Trends (data from: [1, 2, 3])

The recent injection of new powertrain technology is arguably the first radical powertrain innovation in a century and it brings with it significant diversity in design, with manufacturers taking very distinct directions. But as with any innovation that initially sees much divergence, the various hybrid powertrain architectures are likely to converge on a few dominant designs that best suit the application and conditions [5, 6]. Whilst hybrid-electric

*Corresponding author. Engineering Doctorate Student at IDC in Systems.

Email address: Tim.Hutchinson@bris.ac.uk (Tim Hutchinson)

Table 1
Definition of Powertrain Type by Capability

Powertrain Type	Engine Stop/Start	Regenerative Braking	Electric Power Assist	All-Electric Drive Mode	External Battery Charging
Micro Hybrid	✓				
Mild Parallel Hybrid	✓	✓	✓		
Full Parallel Hybrid	✓	✓	✓	✓	
Plug-in Parallel Hybrid	✓	✓	✓	✓	✓
Plug-in Series Hybrid	✓	✓	✓	✓	✓

power is joined by hydrogen fuel cell and all-electric power in the recent powertrain diversification, hybrid powertrains alone shall be considered within this study. The reason for this is that unlike the other systems, hybrid powertrains are now beginning to make a discernible impact on the automotive market and thus a significant number of hybrid designs are now available. This means that it is now possible to explore the relative characteristics and performances of different hybrid architectures through empirical analysis, rather than the largely theoretical work that has been performed to-date.

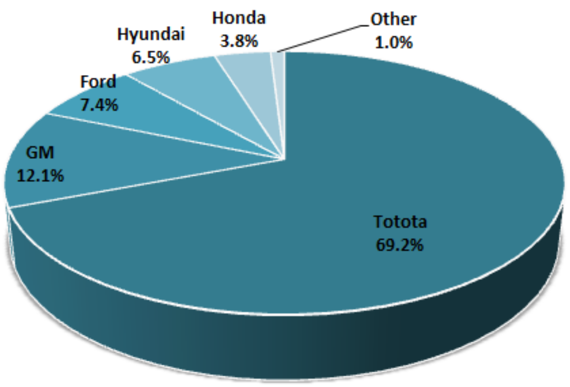


Fig. 2. 2012 US Hybrid Passenger Car Sales by Manufacturer (data from: [4])

Hybrid powertrains can be split into various categories based on their configuration and level of electrification. Table 1 displays the conventional categories that shall be used within this study and their key differentiating capabilities. Due to the commercial nature of this technology, much of the technical information is not easily accessible in the public domain and so this paper seeks to learn as much as possible from a variety of sources and bring it all together into a single review, giving value for both industry and academia. Sections 2 to 6 explore current hybrid vehicles for each powertrain type in turn, looking in detail at the various architecture designs. Section 7 then presents a design and performance comparison of prevailing hybrid architectures applying empirical data collected from the US hybrid market. Finally, Section 8 uses this empirical data to create a whole-life costing model, allowing the relative economic competitiveness to be compared and potential dominant designs to be identified.

2. Micro Hybrid Powertrains

Although not technically a hybrid powertrain due to propulsion coming solely from an ICE, the micro hybrid is often accepted as the lowest level of powertrain hybridisation. It consists of a traditional ICE powertrain but with the addition of a stop-start system that, whilst the vehicle is stationary, switches the engine off rather than leaving it idling and then switches it back on immediately as required. Whilst the technology has existed for several decades, only recently have micro hybrids become commonplace in passenger vehicles, owing to technology refinement and demand for lower fuel consumption. According to the German automotive firm Bosch, which supplies modular stop/start systems to many leading European automotive manufacturers, such systems can typically reduce emissions and fuel consumption by 8%, rising as high as 15% in urban traffic conditions [7].

3. Mild Parallel Hybrid Powertrains

A parallel hybrid powertrain is one with two separate power sources able to directly power the vehicle's wheels. A mild parallel hybrid represents the lowest real level of powertrain hybridisation and it generally requires the smallest amount of bespoke component design. Essentially a mild hybrid consists of an electric motor, of relatively low power output compared to that of the engine, providing acceleration assistance but no all-electric driving mode. Mild hybrids generally also offer start/stop engine idle capability. The most significant variation that can be seen between different mild hybrid powertrain architectures is in the transmission systems, but there are also various energy storage options, with batteries by far the most popular.

The basic mild hybrid architecture essentially involves replacing the engine's starter and alternator motors with a single electric motor/generator that performs the task of both whilst also providing some extra power assistance to the engine. The motor can be directly coupled to the engine, with the rotor acting as the flywheel and it potentially requires no change in gearbox or clutch design, although a continuously variable transmission (CVT) may be chosen for efficiency reasons.

3.1. Systems with Battery Energy Storage

Honda stands out as a pioneer of mild hybrid technology with its Integrated Motor Assist (IMA) system, which has been applied to several production vehicles within its fleet. The IMA system was first displayed in the 1999 Honda Insight, which was based on the Honda Civic but with the development target of halving the fuel consumption [10]. The Civic's engine displacement was reduced by a third to just 1.0 litre and assisted by a 10kW permanent magnet synchronous (PMS) motor attached to the crankshaft and powered by a 144V NiMH battery pack. A CVT was also used to allow the engine to be run at its most efficient. Since the 1999 Insight, Honda has employed the IMA system in a number of its models, refining the technology but making no significant alterations. The US Department of Energy [11] has performed a detailed evaluation of the 2005 Honda Accord Hybrid's powertrain, reporting an unchanged architecture but providing a high level of detail on the electrical components.

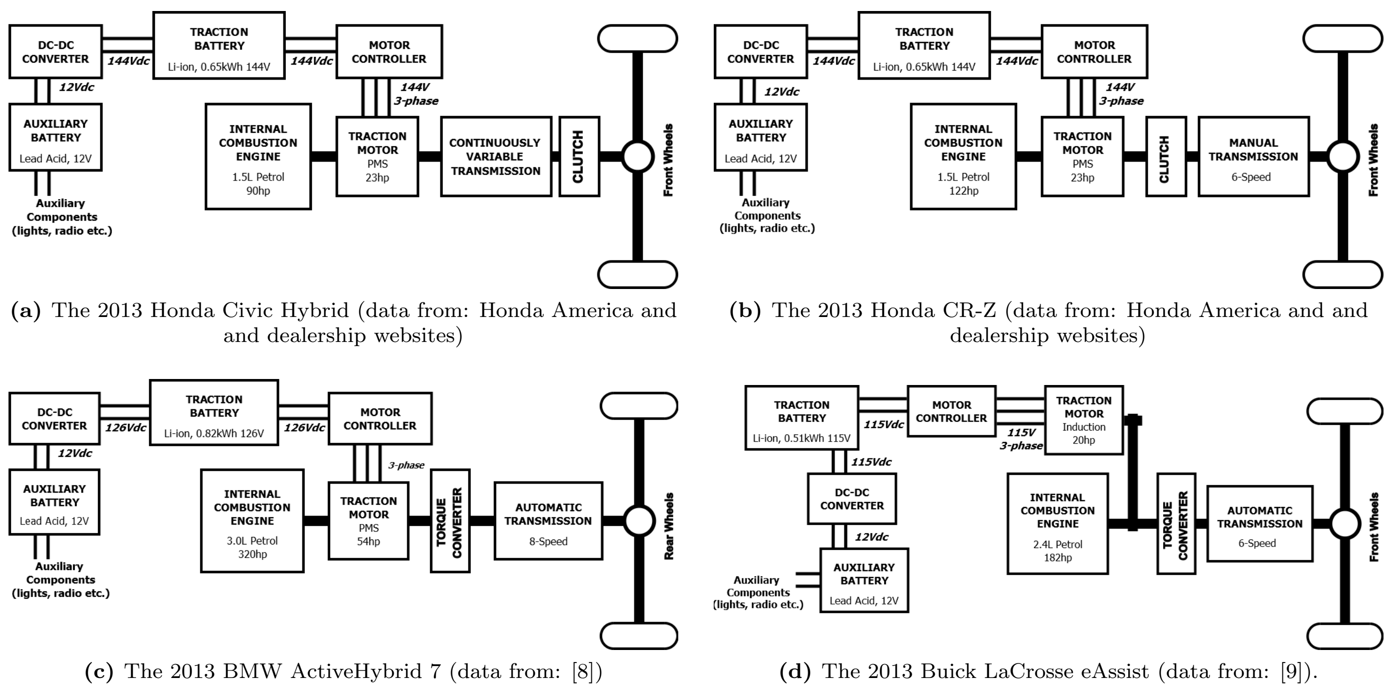
Fig. 3a displays an overview of the powertrain architecture from the current Civic Hybrid model. It is a relatively simple architecture which can be best explained through the three subsystems described below.

- Mechanical System – Consists of an ICE, PMS electric motor and CVT.
- 144V High-Voltage Circuit – Consists of a NiMH traction battery and a PMS motor with matched voltage rating. A conventional controller is also present for motor control.
- 12V Low-Voltage Circuit – Consists of a 12V auxiliary battery which is charged from the traction battery through a step-down dc/dc converter.

Currently, Honda offers the IMA architecture in its Civic, CR-Z, Insight and Jazz hybrid models. The only deviation from the standard configuration is in the CR-Z which is marketed as a sporty hybrid and contains the same electrical architecture but offers a choice of CVT with paddle shifters or manual 6-speed transmission as shown in Fig. 3b. The manual transmission was taken from Honda's non-hybrid Civic model [12] and thus has the advantage of adding to the sporty character of the vehicle without requiring the development resources of a bespoke transmission.

Whilst Honda pioneered mild hybrid technology for passenger cars, it is not the only manufacturer to develop such technology. Daimler and BMW currently offer very similar systems in the Mercedes-Benz S400 Hybrid and BMW ActiveHybrid 7 (Fig. 3c) models but with standard automatic transmissions taken from non-hybrid models.

The only other mild hybrid passenger cars currently on the market are those that use General Motors' eAssist system. The only real difference between the eAssist and IMA systems is that the former couples the motor to the engine's crankshaft through a belt, whereas the latter couples them directly. General Motors considered an IMA style system, but the eAssist architecture was selected on the grounds of being able to accommodate the differing dimensions of an induction motor. Induction motors are



(a) The 2013 Honda Civic Hybrid (data from: Honda America and and dealership websites)

(b) The 2013 Honda CR-Z (data from: Honda America and and dealership websites)

(c) The 2013 BMW ActiveHybrid 7 (data from: [8])

(d) The 2013 Buick LaCrosse eAssist (data from: [9]).

Fig. 3. Distinct Production Mild Hybrid Powertrain Architectures

lower cost than the synchronous motors used in most hybrid powertrains due to a lack of permanent magnets, but they also achieve lower efficiencies. However, General Motors claim that due to the nature of a mild hybrid, the motor is neither motoring nor generating for substantial periods of time and thus the reduction of electro-magnetic field drag losses through using an induction motor offsets the motor's lower efficiency [9]. The eAssist system can be seen in the Buick LaCrosse and Regal models and in the Chevrolet Malibu Eco, which all share the same 2.4l gasoline engine and automatic transmission, as shown in Fig. 3d.

3.2. Systems with Supercapacitor Energy Storage

Although there are currently no production hybrid cars or motorcycles that use supercapacitors (also known as ultracapacitors) for energy storage in place of batteries, they shall be briefly discussed as they have shown potential for improved regenerative braking performance. Supercapacitors have a very high power density, allowing a higher charge rate than is achievable with a battery pack and thus more energy can be recouped during regenerative braking. However, they also have a very low energy density relative to batteries, making them only really suited to the minimal energy storage requirements of mild hybrid powertrains. The current lack in popularity of such systems appears to be largely down to high component costs and added power electronics complexity, although their low energy density is still a very limiting factor.

Whilst supercapacitor systems have not yet appeared in commercial passenger vehicles, the technology has been demonstrated in various forms. Although Toyota does not use such systems in its passenger cars, it has demonstrated the technology's potential through its TS030 hybrid racing car which competes in the FIA World Endurance Championship (WEC). WEC rules stipulate that competing cars may recover 500kJ through braking zones and release it back to the wheels as an engine assist. Whilst Audi opted for a flywheel hybrid system in the R18 e-tron quattro, Toyota chose a supercapacitor based system due to its speed of charge and discharge.

Automotive manufacturer Mazda has made the strategic decision not to invest in hybrid technologies but rather to seek efficiency improvement through refinement and as part of this it has developed the i-ELOOP supercapacitor based regenerative braking system [13]. i-ELOOP does not hybridise the vehicle's powertrain, but it uses similar technologies to increase overall powertrain efficiency. It does this through removing the engine's alternator and charging the auxiliary battery with energy from regenerative braking instead, as shown in Fig. 4.

The potential of supercapacitors has also been demonstrated in hybrid city bus powertrains, predominantly for their excellent regenerative braking capabilities [14], but they have also seen a more novel application. US company Sinautec has developed electric buses which run purely on electricity, but which use supercapacitors to recharge rapidly from overhead cables situated at each bus top.

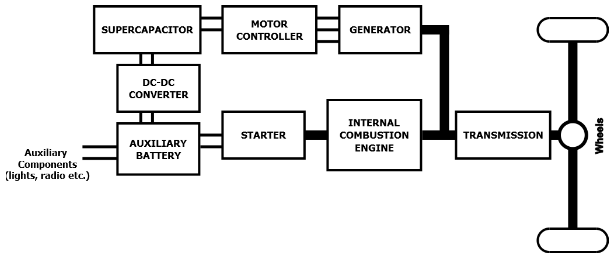


Fig. 4. The Mazda i-ELOOP Regenerative Braking System Architecture

4. Full Parallel Hybrid

A full hybrid powertrain is one that shares all the features of a mild hybrid but with the added capability of all-electric driving, running off electric motors alone. Generally the all-electric mode has its limitations in terms of maximum velocity and reduced acceleration performance, and rarely do such systems have plug-in charge capability, meaning that the battery will ultimately have to be charged by the engine. But with greater electrical energy storage and generally a higher power motor than mild hybrid systems, it creates greater opportunity for the engine and motor to be run more efficiently.

4.1. The Hybrid Synergy Drive

Having sold over 4 million hybrid vehicles worldwide since the original 1997 Prius [15], Toyota undoubtedly stands out as the leading pioneer of hybrid powertrains. For this reason, Toyota has received the greatest critical attention of all hybrid manufacturers, with the US Department of Energy funding a number of research projects aimed at providing an in depth understanding of the Toyota systems [16, 17, 18]. The majority of Toyota's hybrid models are full hybrids and they all share the same fundamental powertrain architecture seen on the original Prius, named the Hybrid Synergy Drive (HSD). The HSD, also known as a power split hybrid, is a relatively elaborate system which is based around an electronically-controlled continuously variable transmission, referred to as an eCVT or power split device, that couples an engine and two motor/generators (MG1 and MG2). Fig. 5 presents an overview of the eCVT. Essentially, it is a planetary gearbox with three inputs/outputs, the carrier, the ring gear and the sun gear which are connected to the engine, MG2 and MG1 respectively. The name eCVT comes from the system's ability to precisely vary the gear ratio between the engine and MG2 by controlling the speed of MG1. MG1 is used predominantly as a generator, charging the battery and powering MG2, whilst MG2 acts as a traction motor, apart from during regenerative braking when it acts as a generator. The eCVT requires neither a clutch nor stepped gear shifting, allowing smooth acceleration across the vehicle's entire speed range. But most importantly, sensitive engine speed control is possible at a range of vehicle speeds by varying the speed of MG1, as displayed in Fig. 5. Control of engine load is also possible by varying the outputs of MG1 and MG2, allowing the system to be run at optimum efficiency.

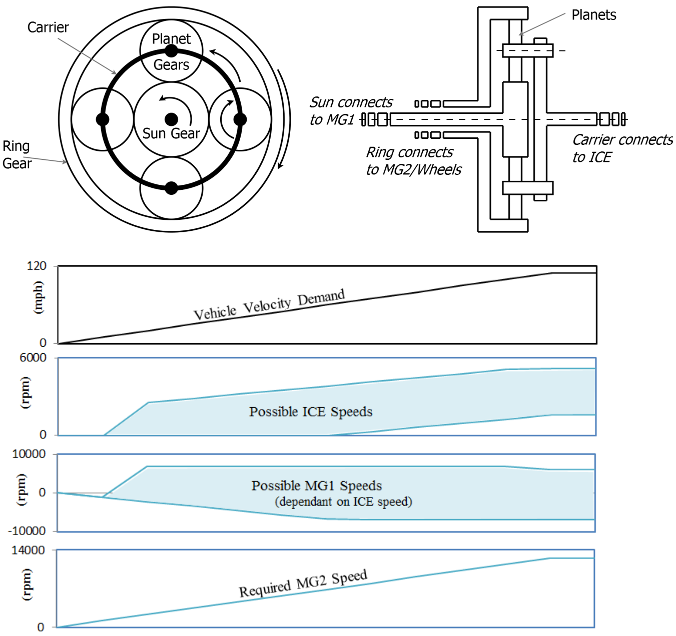


Fig. 5. Overview of the Electronically-Controlled Continuously Variable Transmission (eCVT) as Applied to the Toyota Prius

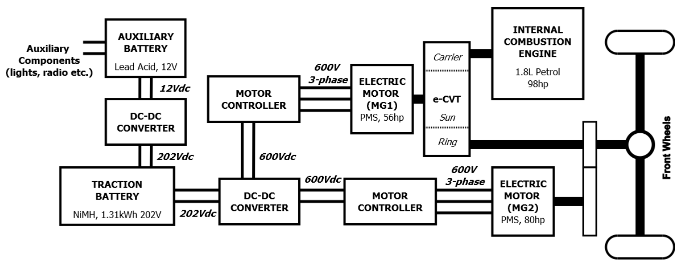
In the original 1997 Toyota Prius, the HSD architecture was named the Toyota Hybrid System (THS). It was then updated to the THS II for the 2004 second generation Prius [19, 20] and finally renamed the HSD when the decision was made to apply the architecture to models other than the Toyota Prius [18]. Each iteration of the architecture's design has seen component refinement but little fundamental change. The greatest improvement is in higher voltage motors offering more efficient performance. An overview of the powertrain from the current third generation Prius model is displayed in Fig. 6a and the three key subsystems are described below.

- Mechanical System – Consists of an ICE, two PMS electric motors and an eCVT. A high-speed reduction gear is required between motor 2 and the eCVT output.

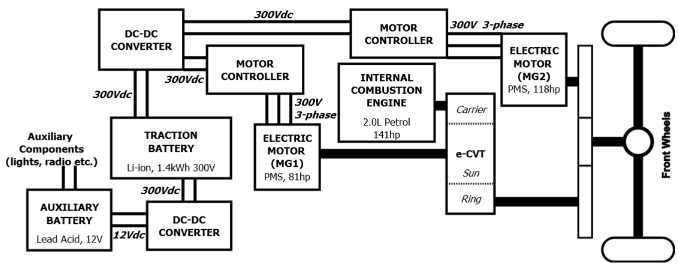
- 650V High-Voltage Circuit – Consists of two 650V PMS motors with separate controllers. The NiMH traction battery is only rated at 202V resulting in the need for a bidirectional dc/dc converter to boost the battery's voltage to 650V. Motor 2 is used for regenerative braking and to power the wheels both in all-electric mode and for engine assist. Motor 1 is used as an engine starter and as a motor or generator as required for eCVT gearing.

- 12V Low-Voltage Circuit – Consists of a 12V auxiliary battery which is charged from the traction battery through a step-down dc/dc converter.

There are several important differentiating factors between the HSD and the mild hybrid powertrains that were discussed in Section 3. Firstly, the HSD requires a bespoke transmission system developed specifically for the powertrain. The system also requires increased electrical componentry, most notably seen in the two high power motors and inverters. Achieving the power requirements of the motors at minimum weight and maximum efficiency requires a high voltage supply. Thus a bespoke bidirectional dc/dc converter is required to step up the battery's voltage, which itself adds additional cost, weight and inefficiencies. Finally, a significantly larger battery pack is required in the HSD system in order to output the required power demand, which also adds minimal, low speed all-electric driving capability. The result of all this is to provide a vehicle with a significant initial cost, but with lower emissions and lower fuel consumption, potentially leading to lower running costs.



(a) The 2013 Third Generation Toyota Prius (data from: [18])



(b) The 2013 Ford C-Max Hybrid (data from: [21, 22])

Fig. 6. Distinct Full Parallel HSD Based Hybrid Powertrain Architectures

Currently, the Toyota Avalon, Auris, Camry, Highlander, Prius, Prius V, Prius C and Yaris models feature the HSD powertrain architecture. The Highlander system differs slightly as it has a third electric motor powering the rear wheels for all-wheel drive capability. Whilst Toyota holds the patents for HSD, it is not the only manufacturer using the technology. Lexus, a subsidiary of Toyota, uses systems based on the HSD in its current CT200h, ES300h, GS450h, LS600h and RX450h hybrid models and Nissan licensed the technology for its discontinued Altima Hybrid model. Ford has also licensed the technology and uses a slight variant on the HSD system in its current C-Max (shown in Fig. 6b) and Fusion hybrid models as well as in the Lincoln MKZ Hybrid.

4.2. The Two-Mode Hybrid

In 2004 a partnership was formed between General Motors, Daimler AG and Chrysler, with the addition of BMW in 2005, tasked with developing new hybrid powertrain technologies [23, 24]. The result was the Two-Mode Hybrid (TMH) system, a hybrid architecture sharing the same eCVT foundations of the Toyota HSD but with distinct functionality. Whilst BMW and Daimler used the system in the BMW ActiveHybrid X6 and Mercedes ML450 Hybrid, they have since discontinued the models and moved away from the technology along with Chrysler, leaving General Motors as the sole user of the TMH. It can be seen in current models of the Cadillac Escalade hybrid, the Chevrolet Tahoe and Silverado hybrids and the GMC Yukon and Sierra hybrids. The characteristics of the TMH make it suitable to very specific uses and thus every vehicle that it has been demonstrated in is a high power, high mass and high cost pickup truck or SUV.

An outline of the TMH architecture is given in Fig. 7. It can be seen that TMH is a significantly more mechanically complicated system than the HSD (Fig. 6a) with the addition of three discrete disconnect clutches and a second eCVT. The powertrain architecture has been explained below through the three key subsystems.

- Mechanical System – Consists of an ICE, two PMS electric motors and two eCVTs.
- 288V High-Voltage Circuit – Consists of a NiMH traction battery and two PMS motors, all sharing the same voltage rating. Two conventional controllers are required for motor control.
- 12V Low-Voltage Circuit – Consists of a 12V auxiliary battery which is charged from the traction battery through a step-down dc/dc converter.

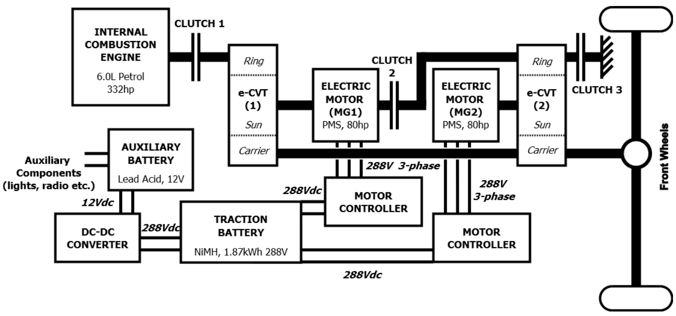


Fig. 7. The 2013 Chevrolet Tahoe Hybrid Powertrain Architecture (data from: [25, 26])

The added mechanical complexity brings with it increased weight and cost, but also increased functionality. As the name suggests, the TMH can be run in two modes, selected automatically through clutches 2 and 3 [27, 28]. Mode 1 is designed for light loads and low speeds. It is selected through the disengagement of clutch 2 and engagement of clutch 3, resulting in the eCVT 2 running as a torque multiplier and the system behaving in a similar manner to the HSD. In mode 1 the powertrain is at its most efficient, running off the motors alone or a combination of the motors and ICE. Mode 2 is designed for higher speed, higher load requirements and it is selected through engagement of clutch 2 and disengagement of clutch 3. Through fine control of the motoring and generating behaviour of both motors, mode 2 varies the powertrain gearing to maintain engine torque multiplication over a range of vehicle speeds. The result is a large, high cost system that allows a powerful, high torque vehicle to run at greater efficiency during low load demand. This is why the TMH has found its place in large, luxury SUVs and pickups.

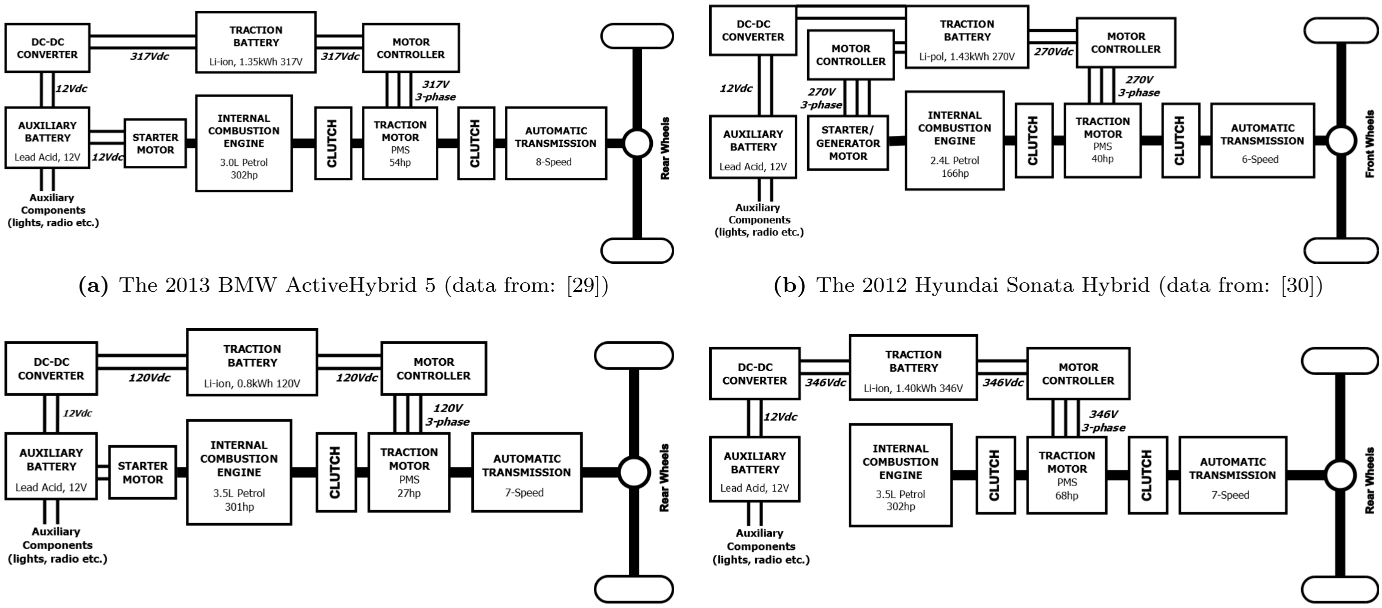
4.3. Inline Full Parallel Hybrids

Whilst the HSD and TMH both require bespoke eCVT transmissions, the majority of full hybrid vehicle manufacturers have opted for less deviation from their established technology. This has led to a range of architectures that are all very similar to the mild hybrid architectures seen in Section 3, with a conventional transmission and a single traction motor. The fundamental subsystems within these Inline Full Parallel Hybrids are as follows.

- Mechanical System – Consists of an ICE, an electric motor and a conventional transmission. The torque converter is generally replaced with a clutch and a second clutch may be necessary depending on mode of engine start-up.
- High-Voltage Circuit – Consists of a traction battery, a single electric motor and a motor controller, generally all sharing the same voltage rating. A high-voltage starter motor may also be used for engine start-up whilst in all-electric driving.
- 12V Low-Voltage Circuit – Consists of a 12V auxiliary battery which is charged from the traction battery through a step-down dc/dc converter. A conventional starter motor may also be used for engine start-up whilst in all-electric driving.

BMW's full hybrid system, seen in the current ActiveHybrid 3 and ActiveHybrid 5 models, is an example of minimum deviation from a non-hybrid powertrain. Fig. 8a displays an overview of the BMW ActiveHybrid 5's powertrain. The torque converter has been replaced by a motor with a clutch on either side, allowing the engine to be decoupled for all-electric driving or the gearbox to be decoupled for engine start-up. A conventional 12V engine starter is also retained to allow a smooth transition from all-electric power to hybrid power.

The Hyundai Sonata Hybrid and Kia Optima Hybrid share a powertrain architecture that has much in common with BMW's. As can be seen in Fig. 8b, the Hyundai/Kia



(a) The 2013 BMW ActiveHybrid 5 (data from: [29])

(b) The 2012 Hyundai Sonata Hybrid (data from: [30])

(c) The 2013 Mercedes-Benz E400 Hybrid (data from: [31])

(d) The 2013 Infiniti M35h (data from Infiniti Europe website)

Fig. 8. Distinct Inline Full Parallel Hybrid Powertrain Architectures

powertrain also places the traction motor between the engine and an automatic transmission, sandwiched by clutches. However, whilst it still has a separate starter motor, it is a more substantial, high voltage motor that fulfills both starter and generator functions.

Mercedes-Benz has used a similar system in its E400 Hybrid model but with only a single clutch outside of the transmission, as seen in Fig. 8c. Since the system has a separate starter motor, the only need for a clutch between the motor and the transmission would be to allow the engine to charge the battery whilst the vehicle is stationary, but it appears that Mercedes has decided this is not a necessary capability.

Both the Volkswagen Group and Infiniti have released hybrid passenger cars with powertrains similar to those of BMW and Hyundai/Kia, but minus the starter motor. Instead they use the traction motor to start up the engine, relying on fine electrical control, but ultimately resulting in a less smooth transition from all-electric mode to hybrid power mode [32]. The architecture is used in the Infiniti M35h (Fig. 8d), the Volkswagen Jetta Hybrid and Touareg Hybrid, the Audi A6, A8 AND Q5 Hybrids and the Porsche Panamera S and Cayenne S Hybrids.

The final full hybrid powertrain architecture that has been identified on current passenger vehicles is found in PSA Peugeot Citroën models. It is a very distinct powertrain architecture that is essentially a cross between traditional parallel and series hybrid architectures. Fig. 9 displays an overview of the architecture seen in the 2012 diesel Peugoet 3008 HYbrid4, which can also be seen in the current Citroën DS5 HYbrid4, Peugeot 508 HYbrid4 and Peugeot 508 RXH models. It is a four-wheel-drive architecture, with the front wheels powered by a diesel engine and the rear wheels powered by a PMS motor. The traction motor is powered by a NiMH battery pack which is charged by a starter/generator module coupled to the engine, essentially creating a series hybrid configuration. It is a sizeable architecture which initially appears rather complicated. However, in many ways it is actually a very simple architecture in that it separates the electrical and mechanical (ICE based) powertrain components. This allows the use of proven powertrain technology at the front wheels with very little modification and it also creates four-wheel-drive capability without the need for a mechanical coupling between the two axles. Audi has presented a similar powertrain architecture in its A5 e-tron concept.

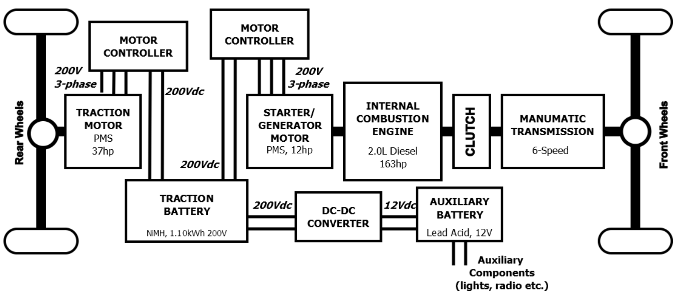


Fig. 9. The 2012 Peugeot 3008 Hybrid4 Powertrain Architecture (data from: [33])

5. Plug-in Parallel Hybrid Powertrains

The unique characteristic of a plug-in hybrid powertrain is that the battery can be charged from an external electricity source, whether it be a mains electricity socket or a dedicated charging unit. This allows the vehicle to be run as an electric vehicle for short journey lengths and as a hybrid for extended journeys.

5.1. Plug-in Hybrid Synergy Drive

Currently, the only plug-in parallel hybrid vehicles on the market are based on the HSD powertrain. Toyota has released a Prius Plug-in Hybrid model which features the same powertrain as the standard Prius seen in Fig. 6a, but with an increased battery capacity of 4.5kWh, allowing up to 11 miles all-electric driving and plug-in charging capability [34]. Similarly, Ford has released the C-Max Energi and Fusion Energi, plug-in hybrid versions of the C-Max Hybrid and Fusion Hybrid models. The powertrain architecture remains as displayed in Fig. 6b, apart from an enlarged battery pack providing 7.6kWh capacity and 21 miles of all-electric driving [34].

5.2. Plug-in Inline Hybrids

Currently Volvo's sole hybrid offering is the all-wheel drive V60 Plug-in Hybrid which uses a similar architecture to PSA Peugeot Citroën (Fig. 9), with a diesel engine driving the front wheels and an electric motor driving the rear wheels [35]).

To-date the one piece of advanced hybrid technology that the motorcycle industry has seen is the Piaggio MP3 Hybrid, a three-wheeled scooter with a parallel hybrid powertrain. Whilst the MP3 Hybrid was not particularly well received in 2009, due to a high cost, low power and high weight [36], it has seen several updates since and is still available in some European markets. Fig. 10 displays the powertrain architecture of the 2010 Piaggio MP3 Hybrid 300ie. The architecture retains the scooter's standard CVT but places a traction motor at the rear wheel, requiring minimal deviation from the established ICE powertrain. The MP3 Hybrid has a claimed all-electric range of 20km and it has plug-in charge capability, with a full charge achievable in around 3 hours from a 12V mains supply [37].

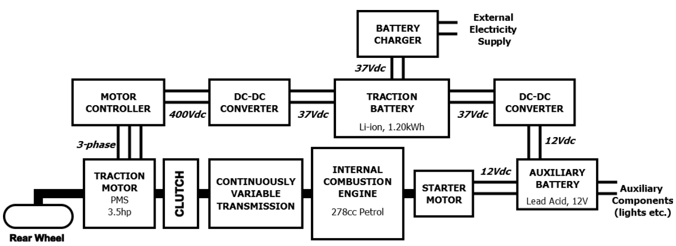


Fig. 10. The 2010 Piaggio MP3 Hybrid 300ie Powertrain Architecture (data from: [37])

6. Series Hybrid Powertrains

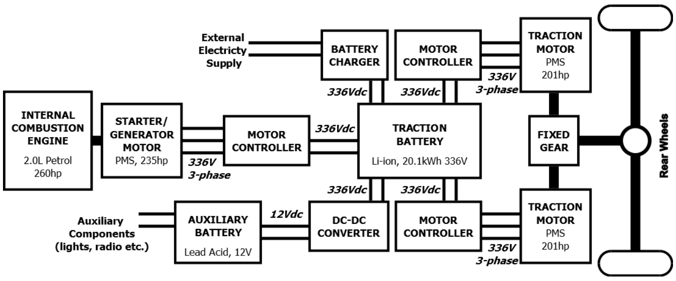
There is inherently less scope for architecture design diversity within series hybrid powertrains than in parallel hybrid powertrains. This is because a series hybrid necessarily consists of particular components in a specific arrangement. The wheels are powered solely by electrical energy, as in an electric powertrain, and an engine is used to generate electricity through a second motor/generator. Generally, series hybrids have a large battery pack which allows reasonable all-electric range and plug-in charge capability so that the engine is only ever required for long journeys. Perhaps due to the large powertrain size and cost, very few series hybrid passenger vehicles have been released.

The only true series hybrid passenger car currently available is the Fisker Karma, a high cost, luxury sports car sold in relatively small numbers to-date. Fig. 11a gives an overview of the Karma's powertrain. It has a very simple layout but one that requires extensive componentry, as explained below through the key subsystems.

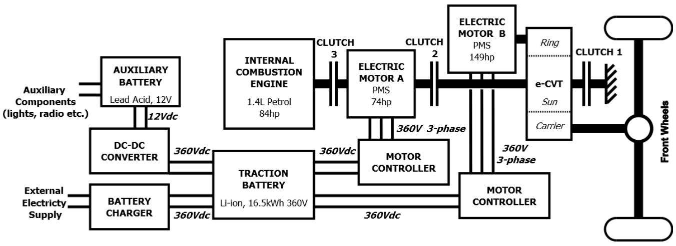
- Mechanical System 1 – Consists of an ICE and an electric generator.
- Mechanical System 2 – Two electric traction motors coupled directly to the rear wheels.
- 336V High-Voltage Circuit – Consists of a large traction battery, two electric traction motors and an electric generator, all sharing the same voltage. Three motor controllers and a battery charger for plug-in capability are also required.
- 12V Low-Voltage Circuit – Consists of a 12V auxiliary battery which is charged from the traction battery through a step-down dc/dc converter.

Fisker claims an all-electric range of up to 50 miles after which the engine must start up. For optimum speed performance and a 0-60mph time of 6.3s, the engine is started and electricity travels directly from the generator to the motors, supplementing the battery charge and allowing a combined motor output of 403hp. Fisker is also applying its series powertrain to the planned Atlantic and Surf models.

The Chevrolet Volt has been promoted as a breakthrough series hybrid passenger car. However, whilst it runs in series for the majority of the time, it does not actually possess a 100% series architecture. Fig. 11b displays an overview of the Volt's Voltec powertrain which is surprisingly complicated for a powertrain sold on its series hybrid capability. In fact it is designed to permit significantly more flexibility over the motor operating conditions than a standard series architecture, allowing higher efficiency to be achieved. As with a standard series powertrain, the system can be run in full electric mode using motor B (clutch 1 engaged, clutches 2 and 3 disengaged), but, uniquely, this can be supplemented by motor A (clutch 2 engaged, clutches 1 and 3 disengaged) in order to limit motor B's speed and thus increasing its efficiency. When battery charge is depleted, range extender mode is used - the engine is started and used to generate electricity through motor A, indirectly powering motor B.



(a) The 2012 Fisker Karma (data from: [38, 39, 40])



(b) The 2013 Chevrolet Volt (data from: [41, 26])

Fig. 11. Distinct Series Hybrid Powertrain Architectures

However, whilst in range extender mode the system fails to be a series hybrid at high speeds - clutch 2 is engaged and mechanical power from both the engine and motor A supplement motor B [42, 41]. The Vauxhall/Opel Ampera shares the Volt's powertrain but with the addition of Hold and Mountain modes [43]. The Hold mode preserves battery charge for later use by starting the engine up early and the Mountain mode charges the battery in preparation for maximum power requirement, for situations such as a steep ascent.

7. Empirical Powertrain Comparison

History has shown that radical innovations tend to see divergence early on, but as the innovation matures the design iterations soon converge on a small number of examples that best fit the application. Hybrid powertrains are a relatively fresh innovation and many automotive manufacturers are still finding their way with their first hybrid systems. This has seen manufacturers boldly striding out in very different directions, creating a diverse range of architecture designs. However, this diversity is unlikely to last as the various powertrains are tested in real-life conditions and dominant designs begin to emerge [5]. Figs. 12 and 13 review the current US hybrid market by market sales and it can be seen that HSD powertrain (including Toyota, Lexus and Ford models) is currently dominating the market. Is this a sign of a dominant design emerging or just a temporary trend?

This section seeks to learn from those architectures that have reached the production phase by comparing their relative specifications and performance values. A whole-life economic model shall then be presented in Section 8 along with a sensitivity study which will attempt to predict those powertrain architectures that are likely to dominate in years to come. The recent rise in hybrid powertrain diversity means that the industry has now reached a stage where this analysis can be performed based on empirical data rather than the largely numerical models that have preceded this study. Empirical data arguably allows a more accurate analysis than can be performed through a numerical model alone and it certainly allows more relevant analysis than has been seen in many of the models published previously. Essentially empirical and numerical models require different sets of assumptions. An empirical model will negate many of the significant assumptions that numerical models require in producing absolute performance values. However, it requires assumptions to be made on the scaling of these values if the performance of a powertrain architecture is to be generalised from an existing example.

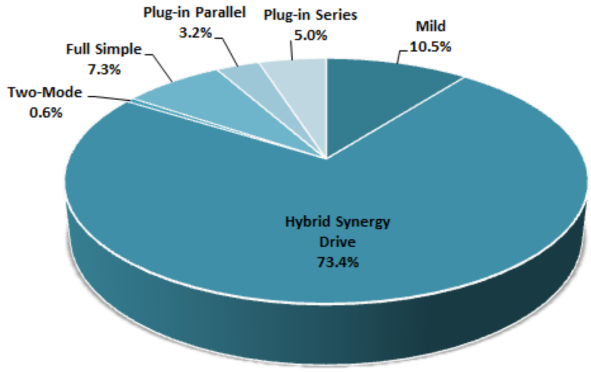


Fig. 12. 2012 US Hybrid Passenger Car Sales by Powertrain Architecture [4]

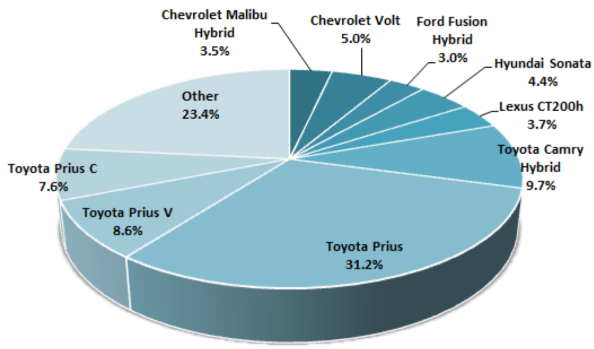


Fig. 13. 2012 US Hybrid Passenger Car Sales by Model [4]

Due to the highly commercial nature of hybrid powertrain research, design and performance information is not easy to come by. Therefore, an extensive review of quantitative data for current hybrid vehicles has been performed, consisting of academic literature, promotional documentation, user documentation, vehicle reviews and communication with manufacturers. Only those hybrid models that are currently available in the US have been considered in this section, as the US has the most diverse hybrid market in the world. This also allows fuel consumption readings from the US Environmental Protection Agency (EPA) to be analysed, which are based on some of the most realistic cycles available and include specific tests for plug-in hybrid vehicles. Table 2 displays the hybrid models that have been included in the analysis, along with comparable conventional vehicles (CVs) and relevant references. Comparable CVs are used to calculate fuel savings using official EPA fuel economy values. They must possess a similar trim, size and mass, and an output power that differs by less than 10%. Average design and performance data has been collected for each architecture type and it is presented in Table 3. As Table 2 explains, several pieces of data were unavailable due to manufacturer confidentiality. Where this was the case, averages were taken excluding these values.

Hybrid powertrains are generally promoted on reduced running costs due to lower fuel consumption, a characteristic that is displayed clearly in Table 3. However, the level of advantage that is gained from reduced fuel costs is dependent on how the vehicle is used, with significantly higher fuel savings in city driving opposed to highway driving. This is a result of the increased opportunities for efficiency increase in city conditions due to greater braking behaviour and speed variation. Although Full Hybrids have the capability of all-electric driving, only Plug-in Hybrids have official EPA all-electric ranges, based on all-electric equivalent fuel economy ratings. This is because full hybrids only have very minimal all-electric capability, available at low speeds and over short distances.

When reviewing the empirical powertrain data for the vehicles in Table 2, a relationship could be seen between traction battery capacity and powertrain output power for non plug-in hybrid architectures. The relationship does not exist for plug-in hybrids, as their battery capacity is no longer driven by system power, but by all-electric range instead. Table 3 presents estimated linear relationships between battery capacity and output power, along with a battery capacity value for a 100kW powertrain. It can be seen that traction battery capacities vary significantly across different hybrid powertrain architectures and appear to be somewhat related to fuel savings. Mild hybrids require the least capacity as the traction motor is relatively low power and they have no all-electric driving capability. The full hybrid architectures require increased capacity for minimal all-electric driving and the higher electric power requirements of the HSD and Two-Mode architectures. Finally, the Plug-in architectures require significantly higher battery capacities for more usable all-electric driving capabilities.

Whilst battery capacity is often used to categorise hybrid powertrain architectures, it is in power distribution that the architectures really display their diversity. Fig. 14 displays the engine and electric motor power requirement for each hybrid architecture, assuming a powertrain output power of 100kW and the power relationships displayed in Table 3. The design diversity is immediately clear and it is interesting to see that the sum of component power outputs is significantly greater than the maximum powertrain power output for most hybrid architectures. This leads to a larger, heavier and higher cost powertrain.

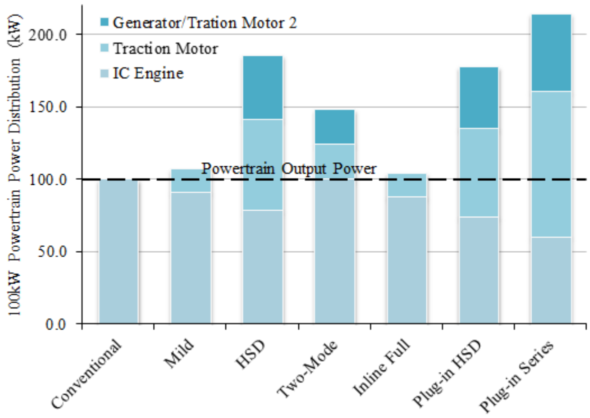


Fig. 14. Powertrain Power Distribution for Different Architectures of 100kW Output Power

8. Whole-Life Costing

One of the most important factors affecting the success of an innovative new product is undoubtedly cost and hybrid vehicles are no different, with customers most often required to pay a premium for the technology. However, whilst the initial cost of a hybrid powertrain is generally higher than that of a conventional powertrain, the running costs can be significantly lower due to higher system efficiency. Therefore, it is important to consider whole-life costs when analysing the economic viability of different powertrains.

8.1. Whole-Life Costing Model

Various costing models have been published for hybrid vehicles in recent years, targeting different hybrid powertrains, with varied results. Plug-in hybrid vehicles have received much attention in particular, as they are seen as being a potential game changer in the industry. In 2006 the US Department of Energy explored the economics of plug-in hybrid vehicles for the US market [47]. It was concluded that, whilst hard to predict variations in key parameters such as fuel and battery prices, it was unlikely that reduced lifetime energy costs alone would justify the increased initial powertrain cost. Lipman and Delucchi [48] performed similar analysis in 2006 but for various mild and full hybrid vehicles, concluding that mild hybrid powertrains in particular were nearing economically competitiveness in the US. However, fuel and battery prices have seen significant changes in subsequent years, potentially invalidating these conclusions. In 2012 Sharma et *al.* [49] explored the economic viability of hybrid vehicles for Australian market. The model considers the main

Table 2
Current Hybrid Passenger Cars Available in the USA

Hybrid Model *(Models that share the same powertrain are included just once)*	Comparable gasoline Hybrid *(Similar performance characteristics and trim level)*	Data References *(Other than manufacturer/dealer website and www.fueleconomy.gov)*
Mild Parallel Hybrid		
2012 Honda Insight	2013 Toyota Yaris 1.5L	
2013 Honda Civic Hybrid *(Acura ILX Hybrid)*	2013 Toyota Yaris 1.5L	
2013 Honda CR-Z Manual	2013 Hyundai Veloster 1.6L	
2013 Mercedes S400 Hybrid[1]	None found	[31]
2013 BMW ActiveHybrid 7	2013 Infiniti M37 3.7L	[8]
2013 Buick Regal *(Buick LaCrosse eAssist, Chevrolet Malibu Eco)*	2013 Buick Verano 2.4L	[9]
Full Parallel Hybrid - THS		
2012 Toyota Camry Hybrid LE[2] *(Toyota Avalon Hybrid, Lexus ES300h)*	2012 Toyota Camry 2.5L	Manufacturer contact
2013 Toyota Highlander Hybrid[2]	2013 Toyota Highlander 3.5L	Manufacturer contact
2012 Toyota Prius *(Toyota Prius V, Lexus CT200h)*	2013 Toyota Corolla 1.8L	[44] Manufacturer contact
2012 Toyota Prius C[2]	2013 Toyota Yaris 1.5L	Manufacturer contact
2013 Lexus GS450h	2013 Lexus GS350 RWD 3.5L	[45]
2013 Lexus LS600h L[2]	None found	
2013 Lexus RX450h FWD[2]	2013 Lexus RX350 FWD 3.5L	
2013 Ford Fusion Hybrid *(Ford C-Max Hybrid, Lincoln MKZ Hybrid)*	2013 Ford Fusion 2.5L	[21, 22]
Full Parallel Hybrid - Two-Mode		
2013 Chevrolet Tahoe Hybrid 2WD *(Chevrolet Silverado Hybrid, GMC Yukon Hybrid, GMC Sierra Hybrid, Cadillac Escalade Hybrid)*	2013 Chevrolet Tahoe 2WD	[25, 26]
Full Parallel Hybrid - Inline		
2013 BMW ActiveHybrid 5 *(BMW ActiveHybrid 3)*	2013 Infiniti M37 3.7L	[29]
2012 Hyundai Sonata Hybrid *(Kia Optima Hybrid)*	2013 Hyundai Sonata Auto 2.4L	[30]
2013 Infiniti M35h	2013 Infiniti M37 3.7L	
2013 Volkswagen Touareg Hybrid *(Porsche Panamera S Hybrid, Porsche Cayenne S Hybrid)*	2012 Porsche Cayenne S 4.8L	
2013 Volkswagen Jetta Hybrid SEL	2013 Volkswagen Jetta 2.5L	
2013 Mercedes E400 Hybrid Sedan	2013 Mercedes E350 Sedan 3.5L	[31]
2013 Audi Q5 2.0T Hybrid Prestige	None Found	[46]
Plug-in Parallel Hybrid		
2012 Toyota Prius Plug-in	2013 Toyota Corolla 1.8L	[44]
2013 Ford C-Max Energi *(Ford Fusion Energi)*	2013 Ford Fusion 2.5L	[21]
Plug-In Series Hybrid		
2013 Chevrolet Volt	2013 Chevrolet Cruze 1.8L	[41, 26]
2012 Fisker Karma	None found	[38, 39, 40]

[1] ICE power and battery capacity data unavailable

[2] MG2 power data unavailable.

Table 3
Average Empirical Design and Performance Values by Powertrain Architecture

Powertrain Type	Architecture	Battery Capacity (kWh)[1]	Motor:Engine Power Ratio	Motor+Engine: Output Power Ratio	City Fuel Savings (%)	Highway Fuel Savings (%)	All-Electric Combined Fuel Savings (%)	All-Electric Range (miles)
Mild Parallel	Mild	$0.53+1.1\text{x}10^{-3}$/kW (0.64@100kW)	0.17	1.07	21.1	15.7	-	-
Full Parallel	HSD	$0.72+5.1\text{x}10^{-3}$/kW (1.23@100kW)	1.37	1.86	43.6	19.5	-	-
Full Parallel	Two-Mode	$0.72+5.1\text{x}10^{-3}$/kW (1.23@100kW)	0.48	1.48	25.0	8.70	-	-
Full Parallel	Inline Full	$0.88+2.4\text{x}10^{-3}$/kW (1.12@100kW)	0.19	1.04	27.7	13.7	-	-
Plug-in Parallel	Plug-in HSD	6.03 (6.03@100kW)	1.40	1.78	49.5	23.8	71.7	16.0
Series	Plug-in Series	18.30 (18.30@100kW)	2.55	2.14	37.1	12.5	72.4	35.5

[1] Battery capacity is estimated for powertrains with power output in the region 70-270kW.

hybrid powertrain categories seen in Table 1, with significant design assumptions and concludes that the considered powertrains are all now offering similar economic performances to conventional ICE vehicles. The most detailed costing model reviewed in this study is that of Al-Alawi and Bradley [50](2013), which analyses plug-in hybrid vehicles in the US market and considers a vast range of costing factors including the cost of charger cable, accessory battery and insurance. A potential drawback to applying this level of detail is the significant number of buried assumptions required for the model due to little empirical data reference. The model considers the time required to make back the initial premium paid for the hybrid vehicle, with results ranging from 3.5 to 10 years, depending on the size of traction battery and the vehicle type.

A significant feature that all these costing models share is the foundation of a numerical powertrain model used to estimate powertrain component sizing and fuel savings. This method of analysis requires numerous and substantial assumptions, which leads to assertions based on significant error. The reason for numerical modelling in place of empirical data is that very few production hybrid vehicles were available when much of this research was begun. However, this is no longer the case and, as displayed in Sections 2 to 6, a diverse hybrid vehicle market now exists. Although the conclusions are now outdated, Lave and MacLean [51] (2002) present a costing model based on empirical data for the second generation Toyota Prius, finding it not cost-effective for US customers. We shall follow a similar model within this study, but expanding it to include the many more production hybrid models and architectures now available.

The whole-life costing model presented in this study shall consider the six prevailing hybrid powertrain architectures presented in Table 3 and a conventional powertrain. It shall apply the empirical data collected in Table 3 to model while-life costs for each powertrain assuming 100kW output power. Market conditions for both the US and the UK shall be considered, as they both possess developed hybrid vehicle markets, with very distinct energy prices. Whilst the US has some of the world's lowest energy prices, the UK represents much of Europe with some of the highest. The purpose of the model is not to present absolute whole-life costs, but rather to explore the relative costs of different powertrain architectures. This allows the most economically competitive powertrains to be identified and potential financial savings to be quantified. With the model's purpose in mind, only those factors that are known to vary between powertrain architectures will be included. The following assumptions shall be applied, leading to the whole-life costing model displayed in Fig. 15.

- Empirical powertrain power distribution and percentage fuel savings are constant under varying output power.
- Transmission costs are constant across all architectures.
- Variation in maintenance and insurance costs between powertrains is negligible.
- Financial incentives are negligible.
- Car tax/registration fee based on CO_2 emissions (as seen in the UK, but not in the USA) is negligible.
- All vehicles follow the same depreciation pattern, resulting in zero monetary value after 130,000 miles (11 years), apart from the value of unexhausted traction batteries.
- Plug-in HSD hybrids run in electric-mode for 85% of city driving and 15% of highway driving.
- Plug-in Series hybrids run in electric-mode for 95% of city driving and 30% of highway driving.

Any whole-life costing model requires significant quantitative assumptions and Table 4 lists the costing assumptions applied to this model. ICE, traction motor and power electronics costs are estimated based on power requirements [52, 44]. Traction battery costs are modelled based on energy capacity and energy costs are based on 2013 market values. The fuel economy ratings of a 1.8L Toyota Corolla are used to represent a 100kW CV, allowing the hybrid powertrain fuel economies to be calculated by applying the empirical percentage fuel savings found in Table 3. Due to current limitation in battery lifetime, it is assumed that traction batteries last only for the standard manufacturer warranty period and replacement costs are calculated based on industry reports.

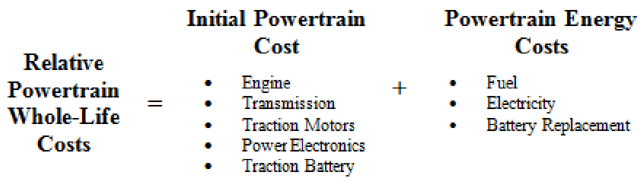


Fig. 15. Whole-Life Costing Model

Table 4
Quantitative Whole-Life Costing Model Assumptions

ICE cost	$531 + $14.5/kW
Motor and Inverter Cost	$425 + $21.7/kW
Battery Charger Cost	$380
Transmission Cost	$12.5/kW
US gasoline cost (2013)	$3.2/gal
UK gasoline cost (2013)	$7.7/gal
US electricity cost (2013)	$0.12/kWh
UK electricity cost (2013)	$0.22/kWh
Traction battery cost (Li-ion)	$500/kWh
Battery lifetime	100,000 miles
Replacement battery mark-up from OEM cost	50%
Battery replacement costs	1.7hrs labour at $125/hr
Replacement battery value after 30,000 miles	50% OEM cost
Powertrain lifetime	130,000 miles
100kW CV Fuel Economy (city/highway/combined)	26/34/29

8.2. Whole-Life Costing at Present

Fig. 16 displays the initial powertrain costs for the different powertrain architectures, broken down into component costs. As expected, a conventional ICE powertrain has the lowest price at around $3,200 and the hybrid powertrains require at least an extra $960 investment. With the largest ICE and motor combination, along with the largest traction battery, the plug-in series powertrain demands the greatest cost, at over £16,000.

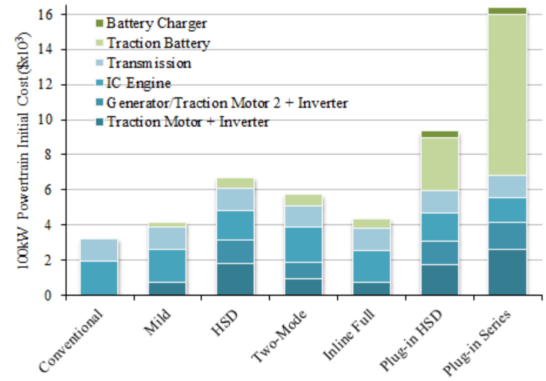


Fig. 16. Initial Powertrain Costs

Having considered powertrain initial costs, Fig. 17 displays the relative energy running costs (gasoline and electricity costs) for the different powertrain architectures in both the US and UK markets. The UK market presents significantly greater opportunity to save money with a hybrid powertrain due to higher energy prices, which is surprising when considering the relative popularity of hybrid vehicles in the two markets as seen in Fig. 1. Perhaps the most prominent feature of Fig. 17 is the city running costs of the plug-in hybrids, at almost a quarter of those for conventional powertrains. But such significant energy savings can only be achieved assuming the majority of city driving can be completed in the limited all-electric range (see assumptions above). So the value seen in these powertrains is clearly dependent on their manner of usage.

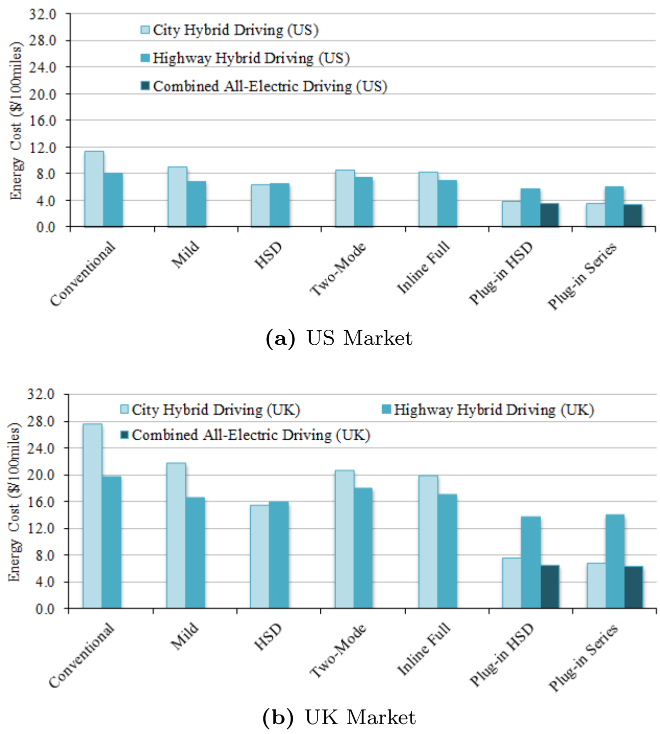


Fig. 17. 2013 Powertrain Energy Running Costs

Table 5
Hybrid Powertrain Financial Savings over a Conventional ICE Powertrain

Powertrain Architecture	US Ownership Savings						UK Ownership Savings					
	Three Years		Six Years		Eleven Years		Three Years		Six Years		Eleven Years	
	City	Highway	City	Highway	City	Highway	City	Highway	City	Highway	City	Highway
Mild	Loss	Loss	$484	Loss	$1,648	$177	$985	$5	$2,931	$971	$6,066	$2,528
HSD	Loss	Loss	Loss	Loss	$2,166	Loss	$604	Loss	$4,689	Loss	$11,269	$695
Two-Mode	Loss	Loss	Loss	Loss	$376	Loss	Loss	Loss	$1,981	Loss	$5,599	Loss
Inline Full	Loss	Loss	$689	Loss	$2182	Loss	$1,366	Loss	$3,898	$348	$7,976	$1,566
Plug-in HSD	Loss	Loss	Loss	Loss	$444	Loss	$137	Loss	$6,390	Loss	$16,465	Loss
Plug-in Series	Loss	Loss	Loss	Loss	Loss	Loss	Loss	Loss	Loss	Loss	$4,232	Loss

Figs. 16 and 17 clearly display that the hybrid powertrains offer very different whole-life costing models to conventional powertrains, with higher initial cost but reduced running costs. But how long does it take for these energy savings to pay back the additional purchase cost? Table 6 presents payback time for the different hybrid powertrains alongside the purchase cost premium that is required. It is assumed that the replacement battery cost is spread evenly across the powertrain's lifetime, as would likely be seen through the vehicle's depreciation. Fig. 18 displays how payback time is calculated. Reviewing the payback times, it is clear that the UK is more suitable for hybrid powertrains and that significantly greater advantage can be gained under city driving conditions compared to highway driving. Only under UK city driving will all the powertrain architectures pay back their purchase cost premium. Table 5 explores how ownership costs of hybrid powertrains compared to convention ICE powertrains vary over time. As with Table 6, it has been assumed that the replacement battery cost is spread evenly across the powertrain's lifetime. An annual mileage of 12,000 miles is assumed, based on US and UK passenger cars statistics, and three ownership periods are presented. Three years is considered as many new vehicles are leased or owned for around this period before being sold on. Six years ownership is roughly half way through a vehicle's/powertrain's usable lifetime and eleven years is considered the usable lifetime, based on current scrappage statistics. It is highly likely that further savings would be achieved if the vehicle were sold on after three or six years, as hybrid vehicles have so far displayed low depreciation trends, lower than comparable conventional vehicles. We shall use the information presented in Tables 5 and 6 to consider the current competitiveness of each hybrid powertrain in turn.

- Mild Hybrids - Have the lowest purchase premium making them attractive for customers who are unable to invest extensively in long-term payback. They will also pay back the initial investment within 3 years in UK conditions, under city or highway driving. However, they do not offer the greatest long-term savings for city driving and payback will take substantially longer under US market conditions. For highway driving they currently offer the most economical solution.

Table 6
Hybrid Powertrain Payback Times

Powertrain Architecture	Purchase Cost Premium	US Payback Time (years)		UK Payback Time (years)	
		City	Highway	City	Highway
Mild	$960	4.0	9.1	1.5	3.0
HSD	$3,480	6.7	Never	2.6	9.0
Two-Mode	$2,510	9.7	Never	3.4	Never
Inline Full	$1,170	3.8	Never	1.4	4.6
Plug-in HSD	$6,120	10.1	Never	2.9	Never
Plug-in Series	$13,150	Never	Never	8.2	Never

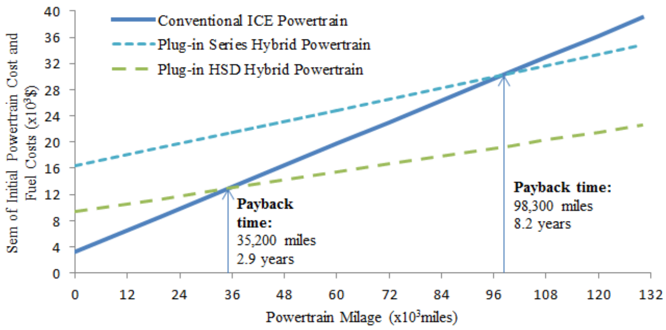
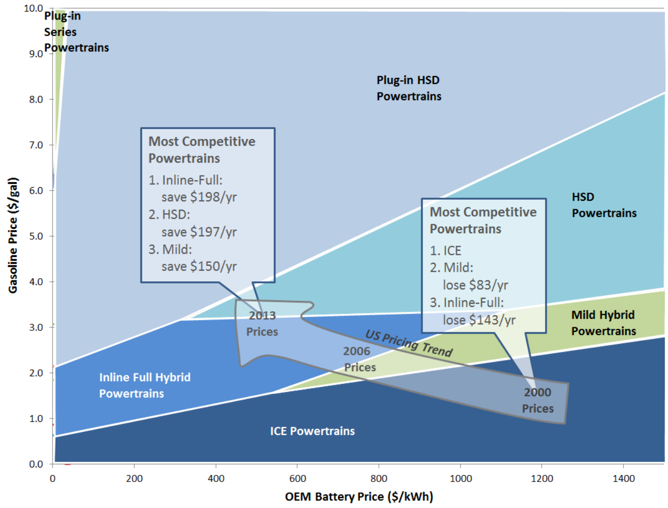


Fig. 18. Sum of Initial Powertrain Cost and Fuel Costs for Plug-in Hybrid Architectures during UK City Driving

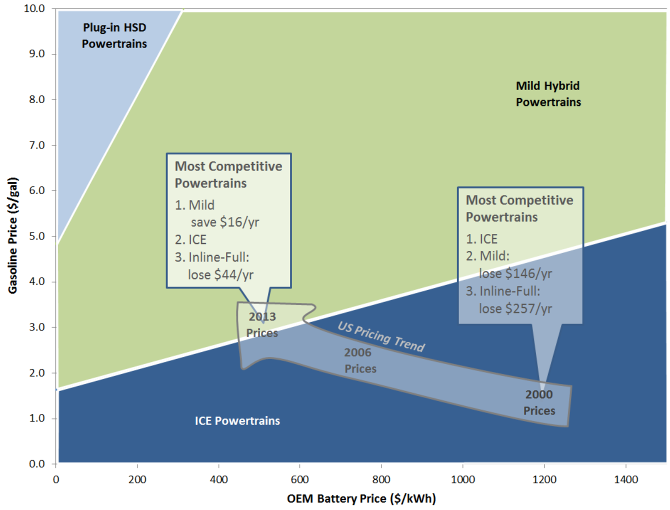
- HSD Hybrids - Require significant initial investment with a purchase premium of almost $3,500, but offer significant long-term savings if used in the UK for majority city driving. Payback time is also quite short under these conditions. They would present very real potential if used for city taxi or courier services. But they do not present a viable solution for suburban use in the US, requiring over 54% city use to provide any saving.

- Two-Mode Hybrids - Require significant initial investment and payback is not swift, especially under highway driving. Do not appear to present a competitive alternative to other hybrid architectures.

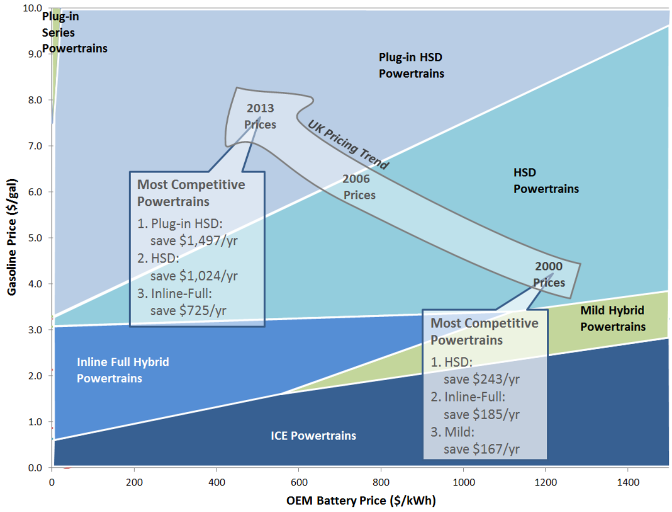
- Inline Full Hybrids - Present a similar option to Mild Hybrid architecture, with a low initial investment and fast payback. Do not perform as well as Mild Hybrids for highway driving, but they offer a slightly more eco-



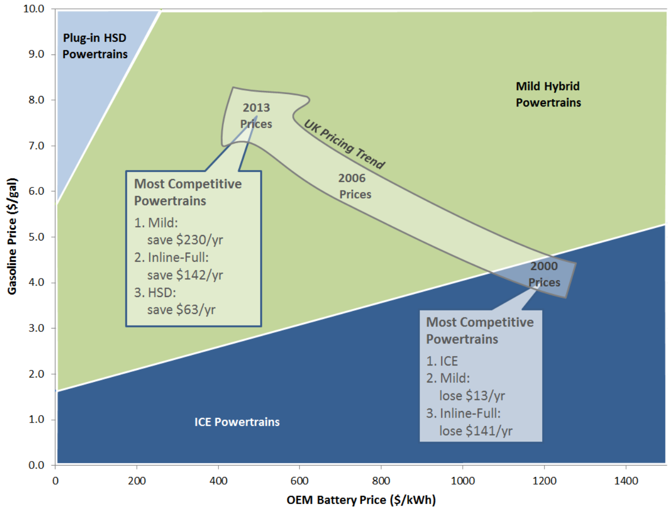
(a) Exclusively City Driving (Current US Electricity Price)



(b) Exclusively Highway Driving (Current US Electricity Price)



(c) Exclusively City Driving (Current UK Electricity Price)



(d) Exclusively Highway Driving (Current UK Electricity Price)

Fig. 19. Most Economically Competitive Powertrain Architectures Under Varying Conditions

nomical solution for city driving. Over 18% city driving is required in the US to see any financial savings.

- Plug-in HSD Hybrids - Require substantial initial investment, almost double that of the HSD, but potentially offer relatively swift payback and highest long-term savings for UK city driving conditions. However, do not present a competitive option for highway driving, especially in the US where over 93% city driving is required to provide any savings, compared to 9% in the UK. Whilst they offer the highest long-term savings under UK city use, this is dependent on the assumptions made for time spent in all-electric mode and thus it will not apply to non-stop driving, such as taxi services.

- Plug-in Series Hybrids - Present the least competitive option, due to very substantial purchase premium and slow payback time. Will not provide any savings under US market conditions and at least 78% city driving is required to see any savings in the UK. Difficult to see what advantage is gained over Plug-in HSD Hybrids, although decreasing battery prices and increasing battery lifetimes will have a significant impact on competitiveness.

8.3. *Whole-Life Costing Sensitivity*

We have considered the current economic competitiveness of the various hybrid powertrains in both US and UK markets. However, the hybrid industry is very fluid and key influences are likely to see much variation in coming years. Therefore, we shall analyse the whole-life costing model's sensitivity to changing conditions, allowing some insight into where the market may be heading and the potential emergence of dominant designs.

Fig. 19 applies the whole-life costing model presented in Section 8.1 to conclude the most economically competitive powertrain architectures over a vehicle's lifetime. Sensitivity to variation in traction battery price and gasoline price is explored for both city and highway driving and recent US and UK market trends are included. The three most competitive powertrains are presented for both current conditions and for the year 2000, with financial savings and losses given relative to a conventional ICE powertrain. As described earlier, it is under city driving that hybrid powertrains really show their strength and this can be seen in Figs. 19a and 19c which show that US and UK markets have seen five different most economically competitive powertrains as market conditions have varied. It appears likely that Plug-In HSD Hybrid powertrains will soon prove most competitive for both markets and for many years to come. Usage behaviour (i.e. typical journey lengths) and availability of charging points will have a significant impact on the success of plug-in hybrid technologies.

Figs. 19b and 19d present a very different picture for highway driving, confirming the sensitivity of hybrid powertrains to their application. Currently Mild Hybrids offer the most economically competitive architecture for both markets, with Plug-in HSD Hybrids a reasonable way off. Declining battery prices may soon lead to Plug-in HSD Hybrids becoming the most all-round competitive solution for the UK market, but a considerable rise in gasoline price and batteries with lifetimes equal to that of the vehicle will most likely be required before the US market sees such a change.

9. Discussion

In the whole-life costing model we have taken a polarised view of vehicle usage by considering city and highway driving separately. The actual usage will generally comprise of a mixture of city and highway driving. However, the model does shine a light on the sensitivity of hybrid powertrains to their application, in a way which is seldom presented to the consumer. Marketing hybrid vehicles is challenging because they offer a very different solution to conventional vehicles, which requires customers to move away from what they are familiar with.

As we have shown, a significant initial investment is generally required from the customer if they are to see maximum long-term savings. However, there are prominent barriers that may prevent customers from making this investment. The customer must possess the financial means to purchase the vehicle and they must also have confidence that the investment will actually realise significant savings in running costs, or that there are significant environmental benefits. Hybrid architectures that require the customer to pay a significant premium could benefit from some sort of battery leasing scheme, as Renault has implemented for its electric vehicles. It is important to note that government-run financial incentives have a significant impact on the economic competitiveness of different powertrains. However, as they are only ever run temporarily, they were excluded from this study.

Hybrid sales figures shown in Fig. 1 contradict the conclusion that high energy costs make UK and European markets better suited to hybrid vehicles, with their popularity significantly higher in the US. There are arguments that this may be put down to greater federal incentives reducing the initial investment impact, fiercer marketing campaigns and more polarised cultural environmental concern. However, from the evidence presented in this study, it appears likely that the European markets will soon pick up and potentially overtake the US if automotive manufacturers can produce more effective hybrid marketing.

Although relatively simplified, the whole-life costing model presented in this study provides an effective means of viewing the current state of the hybrid-electric passenger car industry and the various architectures' relative offerings. The model takes into account the most prominent economic factors that are expected to differ between the different architectures and seeks not to overcomplicate with unnecessary constituents that inherently bring further, hidden assumptions. As with previous costing studies, assumptions were required for component costing based on numerical modelling presented in previous studies. Costing assumptions based on empirical data gathered from current manufacturers would present a more up-to-date, real-life alternative. However, such data is hard to generate due to industry confidentiality barriers. Transmission costing has seen very little attention in cost models to-date and whilst significant disparity between powertrains is unlikely to be seen, further work in this area would be of benefit. With mass production traction batteries yet to run through a whole lifecycle, their scrap value is also currently unknown and may prove important due to high value constituents.

10. Conclusions

A range of significant conclusions have been reached within this study. They are listed below in a concise summary.

- Hybrid car market share is on the rise in leading global markets because of advances in technology and government incentives.
- Hybrid powertrain design has seen significant divergence in recent years, with six distinct hybrid powertrain architectures available today.
- Economic performance is highly dependent on how and where a hybrid powertrain is used. They are significantly more financially competitive when used for city driving opposed to highway driving. Market conditions are also important, with high-cost energy markets such as the UK and much of Europe more suited to hybrid powertrains than the US.

- Whilst a hybrid vehicle may offer substantial whole-life savings, it requires the customer to pay a premium upfront. Therefore, the success of hybrid vehicles is largely dependent on the customer's ability to invest financially and their confidence in long-term savings or environmental benefits.

- Each architecture is suited to different market conditions and the majority require mostly city use to generate any savings. Therefore, higher initial investment does not guarantee greater long-term savings.

- Inline Full and Plug-in HSD Hybrids currently offer lowest whole-life costs for city driving in US and UK markets respectively. Although the economic value seen from Plug-in Hybrids is highly dependent on journey lengths and charging point availability. Under highway driving Mild Hybrids offer lowest whole-life costs in both US and UK markets.

- Bringing traction battery lifetime inline with vehicle lifetime is more important than reducing battery cost for plug-in hybrid powertrains.

- The most likely hybrid powertrain architectures to dominate in future years (from those currently available) are Mild Hybrids, due to low powertrain cost and good highway performance, and HSD and Plug-in HSD Hybrids, due to high long-term city savings.

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