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Current hybrid-electric powertrain architectures: Applying empirical design data to life cycle assessment and whole-life cost analysis

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HIGHLIGHTS

- Design data for 44 hybrid cars available in the US has been gathered and analysed.
- An empirical life cycle assessment of greenhouse gas emissions is performed.
- Empirical whole-life cost modelling is used to evaluate powertrain architectures.
- The value to be seen in each architecture is highly dependent on its application.
- Mild, HSD and Plug-in HSD powertrains are the most likely architectures to dominate.

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ABSTRACT

The recent introduction of hybrid-electric powertrain technology has disrupted the automotive industry, causing significant powertrain design divergence. As this radical powertrain innovation matures, will hybrid vehicles dominate the future automotive market and does this represent a positive shift in the environmental impact of the industry? The answer to this question is sought within this paper. It seeks to take advantage of the position that the industry has reached, replacing previous theoretical studies with the first extensive empirical models of life cycle emissions and whole-life costing. A comprehensive snapshot of today's hybrid market is presented, with detailed descriptions of the various hybrid powertrain architectures. Design data has been gathered for 44 hybrid passenger cars currently available in the US. The empirical data is used to explore the relative life cycle greenhouse gas emissions and whole-life costing of different hybrid powertrain architectures. Potential dominant designs are identified and their emissions are shown to be reduced. However, both the emissions and economic competitiveness of different hybrid powertrains are shown to vary significantly depending on how the vehicle is used.

1. Introduction

The global depletion of natural resources and emissions 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 [1–3]. 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.

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

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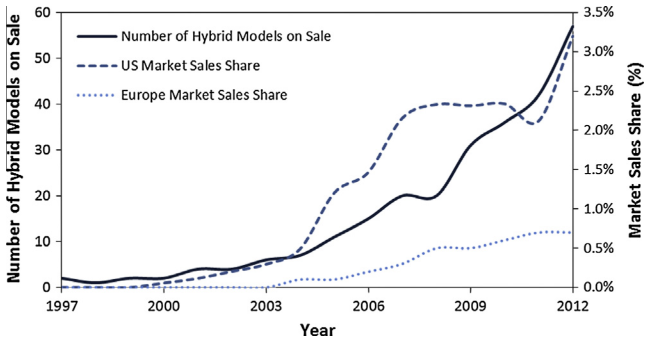

Fig. 1. Historical hybrid market trends.

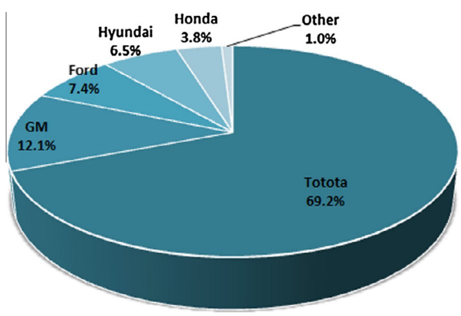

Fig. 2. 2012 US hybrid passenger car sales by manufacturer.

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]. With hybrid vehicles attempting to enter the mainstream, this study seeks to understand whether they can be a viable route to reducing the depletion of natural resources and cutting the emission of environmental pollutants within the automotive industry. Whilst it is clear that hybrid powertrains offer a higher system efficiency than conventional powertrains, this study takes a life cycle perspective in order to understand whether hybrid vehicles provide reduced environmental pollution and whether they have the economic credentials to dominate future markets. Studies have been published on particular hybrid architectures in the past, however this study is the first to consider the entire hybrid market in a life cycle assessment or whole-life costing model. Therefore, the results are directly comparable, allowing conclusions on the relative performances of the different powertrain architectures. It is also the first multiple architecture study to be based on empirical powertrain data, meaning it relies on real-world capabilities rather than the predictions of numerical models. 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 makes it very timely for an empirical evaluation of the hybrid powertrain market and the findings may be crucial in identifying future direction.

This study begins in Section 2 by evaluating the hybrid powertrain architectures that are currently available. 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 in 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 source, providing value for both industry and academia. Section 3 collates and discusses empirical design and performance data for the different hybrid architectures, based primarily on the US hybrid market. Section 4 applies the empirical data to a life cycle assessment of greenhouse gas (GHG) emissions, aiming to identify whether the architectures offer a reduction in emissions. Section 5 describes the development of the whole-life costing model and Section 6 presents the model's finding, looking at relative economic competitiveness and potential dominant designs.

2. Current hybrid vehicle market

2.1. Micro hybrid powertrains

Although not technically a hybrid powertrain due to propulsion coming solely from an ICE, the micro hybrid is often regarded 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].

2.2. 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 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 Hybrid powertrains 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

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	✓	✓	✓	✓	✓