EDITORIAL

Una vez más me dirijo a vosotros, queridos lectores, con el fin de presentaros la nueva edición de Buran. Siguiendo la línea de mejora que hemos trazado, en este número hemos aportado nuevas ideas e intentado mejorar poco a poco. Tal y como se introdujo en la edición anterior, en la penúltima página podréis encontrar la novedades más destacadas.

Este año, celebramos el 25 aniversario de la creación de la Rama de Estudiantes de Barcelona. Para ello, hemos realizado este número especial en el que no existen artículos de diferente temática. Todos giran entorno a un mismo tema: "Los coches híbridos". Debemos agradecer el tiempo de los entrevistados: Adrian Vinsome y Francisco Trinidad. Agradecemos también la atención prestada por el Warwick Manufacturing Group y el trabajo del resto de autores. Hacemos mención especial a Diego Sánchez-Repila, por su paciencia y su esfuerzo. A todos gracias por vuestro tiempo.

Ahora viene la parte más difícil de la editorial. La despedida. Para mí, ha sido todo un honor poder colaborar en la rama de estudiantes y dirigir la edición de esta revista. No sólo ha significado una actividad extraescolar, que realizaba de modo paralelo a mis estudios, sino que ha transcurrido unida a ellos de manera inseparable. Mi camino, como el de muchos otros, continua hacia delante comenzando una nueva etapa. Pero sé que si miro hacia atrás, siempre recordaré con alegría los momentos transcurridos en esta casa. Ha sido una experiencia muy gratificante. Espero poder continuar manteniendo el vínculo que me ha unido a todos mis amigos durante estos años. Sin más me despido, satisfecho de haber aportado mi pequeño grano de arena, y seguro que esta revista queda en buenas manos.

Hasta siempre

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Coordinador de Buran

IMPRESIÓN
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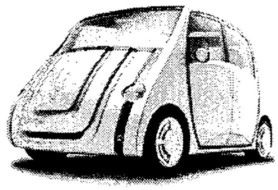

HYBRID ELECTRIC VEHICLES: CURRENT CONCEPTS AND FUTURE MARKET TRENDS

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ABSTRACT

This paper gives a general overview of hybrid electric vehicles (HEVs). Fundamental costs and development within the area of HEVs are analysed in order to show the role that this technology plays in the current automotive market. The advantages and disadvantages of this vehicle technology are also discussed in detail. The paper will also focus on the current and future market projections of HEVs; particularly on the legislative movements which are helping to increase the market share for environmentally friendly vehicles. Opinions of researchers and automotive companies will be taken into account in order to predict which will be the leading technology trends in the future.

Index Terms— Hybrid Electric Vehicles (HEV), Batteries, Hybrids vs. Diesels, Future Trends.

1.INTRODUCTION

Hybrid electric technology has become the latest milestone for the automotive industry such have been diesel technology and the gear system in the past. The growing threat of global warming, excessive petrol dependence, ever increases prices in fuel, and driving trends are just a selection of reasons which have accelerated the development of Hybrid Electric Vehicles (HEV). Also, some government backing has offered support to HEV technology with the introduction of restrictive legislation particularly concerned with the reduction of CO_2 emissions.

The aim of this paper is to observe the initial basis of this incipient technology, analyse the current concepts and discuss the future developments of HEVs by forecasting future events and market sales. Legislative enforcements, different configurations, the breakdown of components, and currently available hybrids will be analysed and discussed in this report with the objective to illustrate all the issues involved with HEV technology.

This publication has been broken down into a number of sections, with a range of areas being covered throughout. The history behind HEVs will be presented, providing a brief picture of the technology. A discussion of what HEVs are, in explaining the current HEV concepts will follow. The motivations behind the move towards this technology will be viewed; showing the reasons why this technology is beginning to grow in stature. The breakdown of hybrid specific components will be mentioned, and the differences between these and conventional configurations will be compared. The way in which HEVs work will be covered along with the operating features of HEV configurations. Current and future HEV models are a key area, and the market status is illustrated and commented upon. There are comparative buying issues between HEV and diesel technologies, and these are analysed and discussed in detail near the end of the work. The publication will conclude with a look at the future trends and summarisation of the key ideas behind this ever growing technology.

2.HEV HISTORY

The competition between vehicles powered by electric and those powered by an internal combustion engine (ICE) is not a new scenario; this antagonism dates back to as early as the beginning of the 19th century. Between 1890 and 1905 ICEs, electric vehicles (EVs), and steam powered cars were all marketed in the United Kingdom and United States. EVs were the market leader in the United States at this time; mainly due to the works of electricity pioneers such as *Edison* and *Tesla*. The limiting range of EVs was not a big problem as the roads linking the cities were not particularly adequate for vehicle transportation.

It was evident that the use of batteries in automobiles was going to pose limitations in range and utility of EVs. Due to the energy advantages of petrol powered vehicles over battery operation, petrol became the dominate energy source over the next 100 years, and is still leading the way today. At the time many automotive companies designed direct ICE vehicles, but some tried to combine the advantages of the electric vehicle with those of an ICE vehicle by creating a hybrid of the two.

The first ever HEV was built in 1898, and there were several automotive companies who were selling HEVs in the early 1900s. The production of HEVs did not last the course of time due to significant problems with them. *Henry Ford* initiated the mass production of combustion engine vehicles; making them widely available and affordable within the \$455 to \$911 price range (H» 375€ to 750€ with prices taken from the current American dollar to Euro conversion rate). In contrast, the price of the less efficient EVs continued to rise. During 1912, an electric roadster sold for \$1,732 (1,425€), whilst a gasoline car sold for \$547 (450€) as illustrated by *About Inventors*. Another problem was the requirement for a smooth coordination between the engine and the motor, which was not possible due to the use of only mechanical controls.

Since these early attempts, there has been a rise in the concern for global warming, a continual rise in fuel prices, and the threat of oil reserves drying up altogether. This had led to interest in more efficient and environmentally means of transport again, particularly in the area of HEV. With advances in battery technologies and onboard computer systems, the option of a plausible HEV has become reality, and a number of models from the likes of *Honda* (*Civic* and *Insight*) and *Toyota* (*Prius*) have been available now since 2000.

There have been a number of prospective designs and HEVs have been growing ever since the inclusion of them onto the world market in 2000. The increased interest along with legislative movements has made advanced clean and efficient transportation not only a vision for the future, but one for today.

3.WHAT ARE THEY?

For the purpose of this work, the definition of an HEV will be as follows:

> «*A Hybrid Ėlectric Vehicle (HEV) is powered by two or more energy sources, one of which is an electrical source.*»

The two most common sources of power in an HEV are mechanical (ICE) and electrical (from batteries). The addition of an electric motor in an HEV means that the size of the gasoline engine can be reduced. The gasoline engine in a hybrid is made to within the specification of the average power requirements of the vehicle, rather than the peak power, this is because the electric motor can provide full operation at low speeds and an acceleration assist when an extra boost of energy is required (high accelerations or climbing steep inclinations). The combination of these two power sources means that the vehicle has the rapid refuelling characteristics of an ICE, and the energy saving capabilities of an EV. The onboard electronics on an HEV can determine whether the gasoline engine, the electric motor, or even both are the most efficient means of use at any given time. In a parallel configured HEV this operation is evident, where both the ICE and the electric motor can provide propulsion power to the transmission. A series configured hybrid differs slightly as the ICE never directly powers the vehicle.

HEVs do not need to be plugged into an external source as all recharging is done whilst the vehicle is in operation. The electric motor acts as a generator through the process of *regenerative braking* in order to recharge the batteries with the energy which would once have been lost through heat and frictional dissipation. *Regenerative braking* occurs whilst the vehicle is slowing down or during idle conditions, such as at traffic lights or junctions. Through the combination of both the direct drive from the engine and the recaptured energy through *regenerative braking* the energy stored within the batteries will be a sufficient amount for the vehicle to operate.

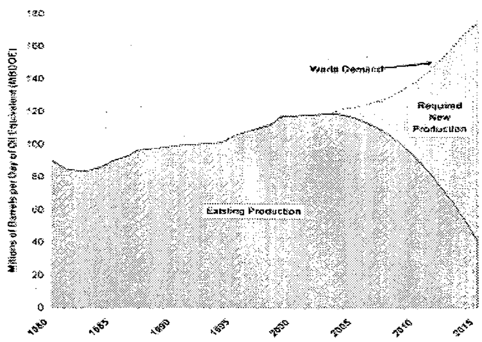

Figure 1: Gas and Petrol Previsions (Source: Exxon Mobil 2004).

4.MOTIVATIONS

The objective of this section is to discuss the key motivations behind the introduction and acceptance of HEVs. A selection of the motivations to be discussed include; petrol dependency, environmental concerns and emissions legislation.

4.1.Petrol Dependency

4.1.1.Resource Supply

The reality that petrol is a finite natural resource is a fact that is often talked about and commonly over looked. It is an area which needs to be addressed sooner rather than later in order to shape the future better in terms of moving away from our dependence of this finite natural resource.

In fact, there have even been predictions into the forecasts of when this resource will eventually run out. *Hubbert* has established himself as a famous analyst due to his successful predictions during his career; one occurrence he rightly determined was the peak in production of American oil in 1978. He has proven that he has superior knowledge due to the successful outcomes of his theories. *Hubbert* has also predicted that in 2019, global oil production will have fallen by 90% of current rates [1]. This could well be the situation we are heading for as all of *Hubbert's* models and theories to date have been correct.

Also, one of the biggest shifts over recent times has been the increase in the price of fuel. In fact, since 2001 crude oil prices have doubled [2]. With the rising uncertainty in the Middle East, it is becoming more of an issue to be less reliant on supplies from this oil stronghold. In contrast to this, the quick development of both China and India has provoked an increasing demand for crude oil.

It can be seen that in *figure 1* that it is possible to compare the newly discovered oil (primarily in Saudi Arabia and Russia) is struggling to match the increase in demand, particularly within the next ten years; where demand will far out way supply. It is becoming imperative to move towards a more efficient means of technology within the automotive industry, in order to keep all these dependences and costs discussed here to a minimum.

4.1.2. Transportation Issues

Away from the on-road effect of which oil has on vehicles, there is the issue of the safe transportation of oil from overseas.

At 3.15 pm on the 13th November 2002, the single-hulled oil tanker *Prestige* loaded with 77,000 tonnes of residual heavy fuel oil, sent out an SOS message at a distance of 28 miles from *Finisterre*, Spain. It was then at 5 pm that the first litres of crude oil began to pollute the Atlantic Ocean [3].

Since this disaster little has changed in legal terms surrounding this issue. The European Union has however forbidden the entry of single-hulled ships carrying heavy fuel into European ports. This type of fuel represents only 5% of all the oil products which enter Europe. Even with these minor efforts in place, the International Maritime Organisation (IMO) has already begun to criticise these timid initiatives.

European coastlines have never before seen the catastrophe which led to over 2000 kilometres of coastline being affected by the oil slick. Hundreds upon thousands of birds were covered in oil, and even to this date oil is still reaching the shores of our European coastlines.

In order to prevent such occurrences from happening again, it is crucial that the dependency and thus mass transportation of oil to be reduced. The *Prestige* disaster must serve as a constructive lesson in order to lead and change the direction of fuel dependence and transportation. The technology of HEVs will lesson the dependency on fuel, and reduce the extent of this risk from happening again. It can not be guaranteed that such an occurrence will never happen again, despite the reduced amounts of oil being shipped, however tighter control methods will ensure that such events would be very unlikely to cause any serious effects to the level of the *Prestige* disaster.

4.2. Environmental Concerns

4.2.1. Driving Trends

Driving habits have changed a tremendous amount over the last number of years. According to an *EU report*, on average each European citizen travels thirty one kilometres every day by car [4]. This figure has grown substantially over the last number of years, from 23.5 km/day between 1991 and 2001, and 16.6 km/day during 1985 and 1986 [4]. According to the same report, the average number of occupants per vehicle is a lowly 1.3 passenger. In the early 1970s this figure was between 2.0-2.1, falling to 1.5-1.6 during the early 1990s.

This decrease over time is a result of increasing car ownership, extended use of cars for commuting and a continued decline in the size of households. The average speed for example in *Barcelona* is a mere 13km/h. In such crowded conditions HEVs would work effectively within this environment. By taking advantage of electric only drive, and the recapture of energy through regenerative braking, these necessary factors would deem the mass inclusion of HEVs a successful venture. One quote regarding driving trends and particularly the usage of vehicles is *«During 2,000 hours usage of a vehicle in Paris, the average time the vehicle is at a complete stop is 700 hours»* [5].

4.2.2. Global Warming

The growing effect of global warming is being made all the more worse with CO_2 emissions from vehicles. In fact, CO_2 is the primary greenhouse gas which increases global temperature. The emissions of CO_2 from vehicles are a huge concern, and there have been a number of research efforts which have gone on in order to fully begin to understand the full extent of the problem [4], [6]. As an example, the emissions of CO_2 from vehicle transport represent 48% of the overall amount of CO_2 produced in the whole of Spain. These scary figures need to be controlled in order to preserve the environmental safety of Spain and the rest of the world.

Increased global warming concerns have coincided with the growing interest in HEVs, and the development of improved battery technologies and integration enhancement. Developments of these sophisticated computer systems will offer greater efficiency benefits whilst providing a smooth coordination between the two propulsion systems. Advanced batteries such as nickel-metal hydride (NiMH) can now provide much higher energy densities and a longer cycle life. These features when used within a HEV can significantly reduce emissions of CO_2.

4.2.3. Emission Legislation

Emissions legislation developments are becoming a motivational development for the technology of HEVs [9]. It has become necessary to create a future regulatory plan to warrant a suitably clean world to live in. The *Kyoto* protocol is one of the main agreements which have been agreed upon by the majority of the countries in the world. The pact requires that industrialised countries must reduce their greenhouse gas emissions to 8% of those levels during the 1990s, between the years 2008 and 2012 [10].

There have been differing approaches in the EU, US and Japan for the regulation of emission laws. The greatest change has been registered in the diesel segment due to the major pollution comparisons which this has with gasoline engines. In *figure 2* the increase in the limits of diesel mechanics from 2000 to 2012 in the EU, US and Japan can be seen.

The further development of strict standards in the US must take into account that the diesel market share only represents 1 to 2% of the total number of

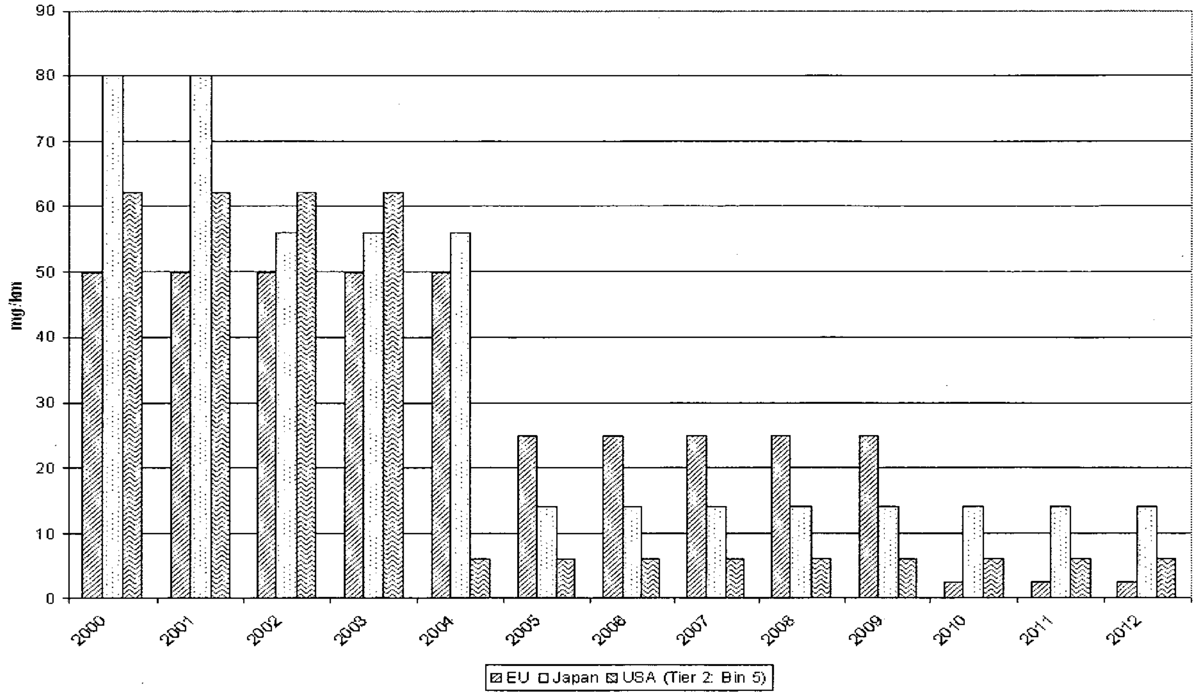

Figure 2a: CO_2 Emissions Limit Forecasts

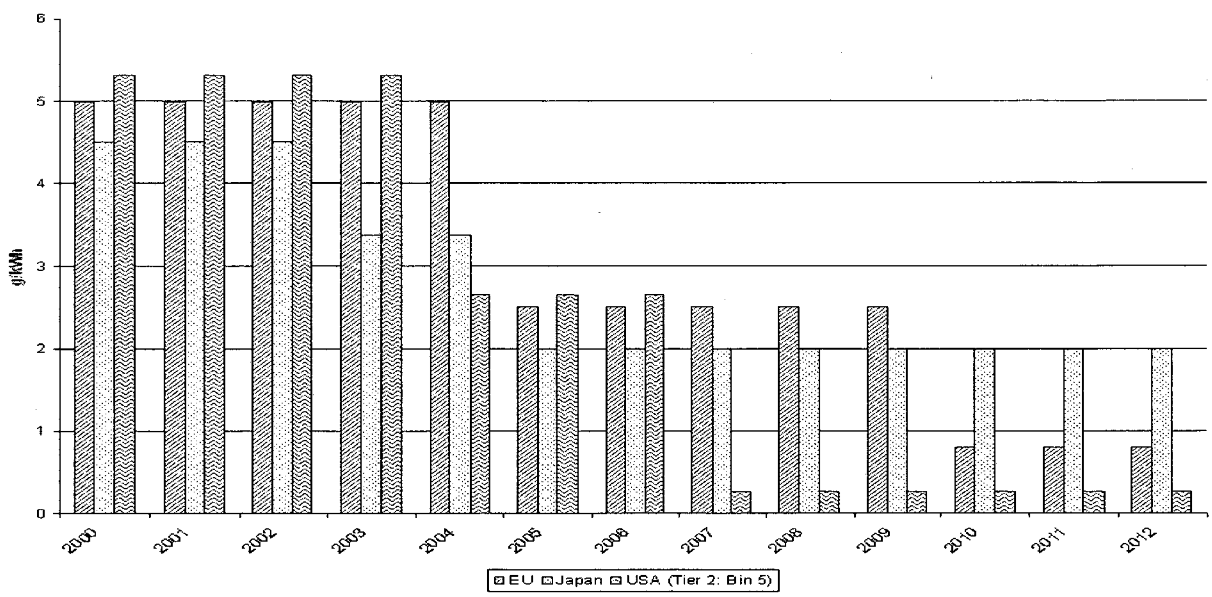

Figure 2b: NOx Emissions Limit Forecasts

Figure 2: Emissions Limits Forecasts for Diesel Engines in Europe (Source: Ricardo Consolatory

vehicles sold, with the majority being imported from European manufacturers such as *Volkswagen* [11].

Europe has an established tradition behind diesel technology, and it is not possible to follow exactly the same approach regarding emissions regulations as has been done in the US. In Europe, targets have been set to lower the limits of CO_2 emissions to 140 g/Km by 2008, and reduce these still further to 120 g/Km by 2012. The current average levels of CO_2 emissions stand at 162 g/km.

Clearly it can be observed that emission legislation is becoming more and more focused on improving the environmental state of the automotive industry. The adoption of more increasingly stringent

TABLE I
HEV BATTERY PERFORMANCES

Battery Type	Max. Energy Density (Wh/kg)	Max. Power Density (W/kg)	No. Of 80% Discharges Before Replacement	Estimated Large-scale Production Cost (€ per kWh)	Anode Material	Cathode Material
Lead-Acid (Pb)	35	150	1,000	51	PbO_2	Pb
Advanced Lead-Acid (Pb)	45	250	1,500	161	PbO_2	Pb
Nickel-cadmium (Ni/Cd)	50	200	2,000	250	Ni	Cd
Nickel-metal Hydride (NiMH)	70	200	2,000+	205	Ni	Metal Hydride
Lithium-Ion	120-150	120-150	1,000+	125	Carbon Intercalation	$LiCoO_2$

Source: "*The Electric Car: Development and future of battery, hybrid and fuel-cell cars*", by M. H. Westbrook, Report of the Institution of Electrica Engineers (IEE), 2001.

laws will enable these targets to be met, and help to maintain the healthy state of the planet

4.2.4. Health Effects

There are a number of health complaints which can be caused by the emissions from vehicles. Respiratory problems increase a person's risk of cancer-related death, and can also contribute to birth defects or make healthy active children 3 to 4 times more likely to suffer from asthma. These are just a selection of problems which can stem from the pollution from vehicles, particularly CO_2 emissions. Even experts have forecasted a number of new diseases provoked by the high concentration of CO_2 [7].

Another form of vehicle related effect is acoustic pollution. Loss of hearing, high blood pressure, sleep deprivation, productivity loss and a general reduction in the quality of life can all develop from the noise of traffic. The greatest and most concerning effects do stem from larger vehicles; including buses and trucks. There has been research into the inclusion of HEV buses, primarily within the US, which has helped to reduce the problem caused from conventional buses [8].

It can be seen that much sickness is caused from the vehicles that people drive. A number of governments worldwide have begun to realise that issues such as these need to be prevented. By regulating tighter measures it will lead to more efficient and environmentally friendlier vehicles.

4.3. Conclusion

In conclusion, it can be seen that the continual rise in fuel prices during the nineties along with the tax advantage of diesels has had a significant effect on the sales of diesel vehicles, especially in the EU. However, on the wider scale, it is becoming more evident that global warming and vehicle pollution are factors which need to be controlled better. These concerns have to date provoked the introduction of more hardened emission legislative laws, especially for diesel vehicles. In order to have a lesser dependency on the increased price of fuel and to operate a more environmentally ***friendly vehicle the technology of HEVs would more than help to satisfy these requirements.***

5. COMPONENTS

5.1. Gasoline Engine

The gasoline engine in a HEV is similar to that found in a conventional ICE vehicle. Gasoline engines in HEVs are usually much smaller than ones found in comparable conventional vehicles. Larger engines are primarily heavier, requiring extra energy during accelerations or climbing inclinations; pistons along with other components are heavier in a larger engine, which decrease the efficiency and add to the overall weight of the vehicle. The gasoline engine is the primary source of power for the vehicle, and the electric motor is the secondary source of power. The *Toyota Prius* for example can operate in stand alone electric mode at low speeds (usually up to 15 mph), and can offer assistance during heavy acceleration or when a power boost is required.

Honda's HEVs do not have an electric-only mode unlike the *Toyota Prius*, though during stops at junctions and at lights the ICE automatically shuts off, and only starts again the accelerator is pressed. The *Honda Civic* incorporates *Integrated Motor Assist* (IMA), which couples both the gasoline engine and the electric motor, to offer boosts in both performance and fuel economy of the vehicle.

Studies have gone on in the development of ICEs for HEVs to further optimise the performance of them; one such study has developed an optimised *compressed natural gas* (CNG) engine for a hybrid urban bus [12]. Both gasoline and diesel engines do have a number of advantages over other competitors and alternative technologies. One key issue is that liquid fuels have extremely high energy densities and can achieve a long driving range for a relatively small storage tank. Another factor is that there are fully established and functional infrastructures for these fuel types; it would cost billions of euros to make changes to the current infrastructure in order to introduce new technology types and alternative fuels. These few advantages alone make it a daunting task for any alternative technology such as fuel-cells to be considered for the short and medium-term solution to a more efficient and emissions free future for transport.

5.2. Electric Motors

The electric motor is primarily used to drive HEVs at low speeds, and assist the gasoline engine when additional power is required. The electric motor can even act as a generator and convert energy from the engine or through *regenerative braking* into electricity, which is then stored in the battery. This functionality works as the electric motor applies a resistive force to the drivetrain which causes the wheels to slow down. The energy from the wheels then begin to turn the electric motor, making it operate as a generator, converting this normally wasted energy through coasting and braking into electricity.

5.3. Generator

In a series configured HEV (discussed later) only the electric motor is connected to the wheels. A series HEV has a separate generator which is coupled with the gasoline engine. The engine/generator set supplies the electricity required by the batteries, in turn feeding the electric motor. The coupled generator and engine maintain the efficient usage of the battery system during operation.

5.4. Energy Storage

5.4.1. Battery Technologies

The batteries are an integral component within HEVs. Electrical energy can be drawn from the batteries to the electric motor; also this process can operate in reverse by recapturing energy through *regenerative braking*. The only time there is a large requirement for electrical energy is during electric only mode, the majority of the time the electrical loads are easily managed within the whole vehicular system. Due to the high cost increment of the battery for energy storage, it is far more cost effective to use the engine as the primary power source for the vehicle at higher loads, rather than increasing the amount of energy storage. Continued efforts must concentrate on improving the existing battery technologies in order to make them more efficient, rather than just increasing their sizes to gain a greater output. By improving the current battery technologies which exist, the costs of HEVs will be kept to a minimum, preventing them from being too high for potential customers to consider.

Table 1 displays the properties as regarding the key battery technologies for hybrid applications, [13]. The following section will discuss the varieties of battery chemistries available; comparing and contrasting between the appropriate types, to determine the most suitable technology for HEV use.

a) Lead-Acid (Pb)

Lead-acid (Pb) batteries were invented by *Gaston Planté* in 1859 [13]. *Gustavo Trouvé* first used them in a vehicle in France in 1881 by demonstrating their use in a tricycle which travelled at 7 mph. Lead-acid is still the most commonly used electrical storage technology for electric traction applications today. One of the main factors in choosing Lead-acid is the lowest costing technology compared to that of other battery chemistry types.

However, due to their low power densities compared to other slightly higher densities offered by alternative battery types, problems occur when there is a high power requirement for their design. In order to meet such high power demands larger battery packs can be constructed, which is not the optimal choice due to the inefficiencies caused by the increased weight and cost of such a development. Lead-acid technologies are not best suited to cold weather conditions because the battery is severely affected under low ambient temperatures of anything below 10 °C. By exposing this technology to such low temperatures it can have damaging effects by reducing both the effective energy and power densities of the battery. A way in which to enable this technology to work under such conditions would be to have battery heating device in operation. A heating device would be able to maintain the temperature of the battery and allow it to operate in this state.

Due to their costs, they are currently the most sensible option to use in low power start/stop systems, which do not require the need to store a vast amount of energy. A simple idle-off system would be an ideal application for this technology. If the requirement however is to achieve a significant amount of electric motor assist and regenerative braking then another battery technology are currently more viable.

b) Advanced Lead-Acid (Pb)

In order to overcome some of the pitfalls of the conventional lead-acid battery type developers have engaged in new techniques in order to produce *advanced lead-acid* batteries. Some of the methods used include improved computer analysis and enhancements to modelling of the urrent distribution in the batteries.

The authors are members of the Technology *& Information Group (TIG)*; a research group based at the University of Warwick has been involved in a number of projects engaged in improving current lead-acid technologies. One project they have been involved with was *RHOLAB (Reliable Highly Optimised Lead Acid Battery)* [14]. The aims of the project were to develop a traction battery suitable for use in an HEV such as the *Honda Insight*. Instead of developing a new type of battery technology, *RHOLAB* took the existing lead-acid battery technology and developed it, so that it could be used in new applications in vehicles of the future. *TIG's* key contributions were with the application of built-in intelligence, module design, case development and the fabrication of a battery management system (BMS). Building on from the findings and experience gained during the *RHOLAB* project the *ISOLAB (Installation and Safety Optimised Lead Acid Battery 42V)* project followed in its footsteps. The *ISOLAB* project aim is to develop a battery capable of meeting the electrical power demands of future vehicle, which is also able to support alternative installation and packaging strategies [15].

Research efforts in Lead-acid technologies have helped to improve the grid structure of current configurations. Battery weights have decreased on the whole, which has resulted in lower internal resistance which can achieve a better retention of the active plate material. A specific example in the development of *advanced lead-acid* batteries is the *Valve-regulated Lead-acid* battery (VRLA). The VRLA battery is the result of a collaborative effort between lead producers, battery manufacturers and component suppliers formed in 1992; whom joined forces as the *Advanced Lead-Acid Battery Consortium* (ALABC) [16].

The key aspiration of the *ALABC* was to improve the specific energy of these batteries, improving their range per charge. Regardless of the additional improvements, VRLA batteries still have a relatively low power, density and cycle life. Lead-acid still has the potential of being a significant battery technology, and there has been research into the possible future developments of the chemistry [17].

c) Nickel-Cadmium (Ni/Cd)

Nickel cadmium (Ni/Cd) batteries were first developed in the early 20th century. They are constructed in a cell configuration with a sintered positive nickel electrode and a plastic-bonded cadmium negative electrode. This battery technology has an energy density of approximately 50 Wh/kg and a relatively high power density of 200 W/kg. This technology has sparked interest in the past with EV developers due to its capability to accept high charge and discharge rates. One problem Ni/Cd has is that such charge capabilities require the use of a carefully control management system to control the battery's temperature, voltage and time of charge and this adds to the cost and weight of a vehicle design. Ni/Cd batteries suffer problems when they are not discharged or recharged fully, as they tend to remember state-of-charge (SOC) extremes, meaning they behave as though they have less capacity.

Due to the increased toxicity of nickel-cadmium over lead-acid the technology is poor in terms of its recyclability. Cadmium products need to be clearly labelled in order to aware people that they need to be recycled or disposed of properly. If this task is not easily achievable then this must be carried out by a professional. This along with a number of other problems has inhibited the use of this battery type and has made other battery types a more viable means for HEV applications.

d) Nickel-metal Hybrid (NiMH)

Nickel-metal hydride (NiMH) has become the long-term replacement for nickel-cadmium (Ni/Cd) batteries, and has appeared in a selection of EVs that have recently been developed. NiMH batteries maximum energy density of 70 Wh/kg is 20 Wh/kg greater than that offered by Ni/Cd types; this is a valuable asset as the battery can be of less weight and still achieve the performance requirements of the vehicle. NiMH can cope with over 2,000 80% discharges before needing to be replaced whereas Ni/Cd needs to be replaced after a maximum of 2,000 cycles. The other advantage NiMH has over Ni/Cd is the fact it is £30 cheaper per unit cost (£ per kWh), this without the toxicity problems of Ni/Cd [18]. NiMH batteries have a greater power and energy density than that of lead-acid types. They have been under development since the 1970s. The energy density of NiMH is roughly twice that of lead-acid batteries, 70 Wh/kg for NiMH compared to 45 Wh/kg for lead-acid [13]. Another advantage is that NiMH batteries can be fully recharged within about 15 minutes.

NiMH batteries are perfectly suited to high-power hybrids, and have been the battery choice for HEV models released to date, of which includes the *Toyota Prius*, *Honda Civic* and the *Honda Insight*. The key reasons why NiMH technologies have been used in the development of HEVs rather than lead-acid is they can offer higher energy and power densities, reduced size mass, longer cycle life and lower cost of ownership. All of which is illustrated in *Table 1*.

e) Lithium-Ion

Lithium-ion batteries have an even higher energy density than that of NiMH batteries. NiMH batteries can offer a respectable 70 Wh/kg, whilst lithium-ion can offer roughly two times that amount ranging between 120-150 Wh/kg. Lithium-ion has a reasonably low maintenance, offering an advantage that most other battery chemistries cannot. There is no memory or scheduled cycling requirements in order to prolong the overall life of the battery.

Despite the obvious advantages of lithium-ion technology, a number of current drawbacks prevent the technology replacing other current chemistries. Lithium-Ion is a fragile technology, which requires a protection circuit in order to maintain the safe operation of the technology type. The inclusion of a protection circuit does however ensure the voltage and current limits remain within their safe limits. Lithium-Ion batteries become susceptible to aging especially when not in use, and are 40 percent more expensive to manufacture than Ni/Cd. Lithium-Ion is currently not a fully matured technology and the chemistry is changing on a continual basis. It still requires huge developments in cycle life, durability, and cost, before the chemistry could become commercially viable and be included in HEVs.

The development of lithium-ion systems have already occurred in research attempts including [19] and [20]. Lithium-Ion technologies are currently used in a number of applications including laptops; cycle life of the chemistry type is expected to improve within the near future. Looking at the wider scale, lithium-ion may not be the breakthrough the automotive industry is looking for, which is essentially crucial in order to be able to reduce the cost of energy storage in HEVs.

5.4.2. Future Energy Storage

There are a number of demands for a HEV energy storage system, a number of which include: high specific energy and power to be able achieve range and performance requirements, long cycle and calendar life (comparable to that of the overall life of the vehicle), quick recharge capabilities, high efficiency, and low cost and maintenance free. Technologies to date which have been deemed suitable for this application are lead-acid batteries, nickel-cadmium batteries, nickel-metal hydride batteries (covered in the previous sections), supercapacitors, flywheels, and hydrogen storage in nanofibres and nanotubes. HEVs energy storage technologies can be split up into three main areas: electrochemical buffers, electrical buffers and hydrogen storage. According to research, the current electrochemical battery options are being implemented and are universally accepted [21]. The battery technologies currently leading the field have already been discussed. Further storage devices of both electrical buffer and hydrogen storage types will therefore be discussed in this section.

The *supercapacitor* or *ultracapacitor* (electrical buffer) is a storage technology which stores a charge within a cell arrangement. Supercapacitors are more commonly known as *Electric Double Layer Capacitors (EDLCs).* Energy is stored within a boundary layer that is formed between the interfaces of a conductive electrode and an electrolyte solution. The interface of the electrode/electrolyte has a very small dielectric thickness (a few Angstroms) and combined with a material of high surface area can produce a low-voltage, high-capacitive, energy storage capacitor.

Supercapacitors have a low resistance and can therefore offer greater power and efficiency compared to that of pulse batteries. They can be produced in large cells, which make them a suitable technology for automotive applications. Supercapacitors have traditionally been created with carbon electrodes which when treated can offer a particularly large surface area of up to 2,000 square metres per gram. These electrodes are typically combined with dilute sulphuric acid electrolytes. The benefits of using an aqueous acid such as dilute sulphuric acid are that they offer high capacitance and power density. A salt solution however, can be used instead if there is a higher preference for a greater energy density than power density. Within a supercapacitor cell the electrolyte is in intimate contact with the electrode of high surface area. The voltage of the cell is limited to just over one volt in order to avoid any chance of decomposition of the water in the dilute electrolyte to oxygen and hydrogen.

The sole use of supercapacitors for the power requirements of an electric vehicle of any form seem to be a number of years away; due mainly to the considerable development requirements of the technology. Supercapacitors would however be a more than viable means to operate in combination with existing batteries due to their high power densities. Supercapacitors can now offer power densities up to 4kW/kg, which is 16 times that of the closest battery power density of 250W/kg for advanced lead-acid types. The combination of the two would work well together as batteries tend to have high specific powers but a much lower power density. These benefits along with the fact they are relatively inexpensive, can be recharged easily (externally or through regenerative braking) and that they require no maintenance because their deterioration over time is far less than that of existing battery technologies; making them a serious consideration when developing such vehicles.

The *flywheel* energy storage system is a mechanical device which can be regarded as another electrical buffer, which stores kinetic energy within a rapidly rotating wheel rotor. They contain no hazardous chemicals, and are not affected by high rises in temperatures, unlike some battery technology types. Flywheels are a technology which has been around for a number of years, but with performance capability developments, have recently been able to compete with electrical battery storage systems. Currently prototype flywheels are considered too large and heavy for small HEVs, although efforts are currently being made into being able to produce new lightweight, high strength materials for flywheels. However, due to the level of complexity, and the costs in producing an efficient unit may exclude there use in hybrid vehicles altogether.

Hydrogen storage technologies are the other key area in future storage options. *Primary Hydrides (the Millennium cell)* are based on the reaction between aqueous alkaline sodium borohydride and high surface area metal catalyst. The reaction within this cell is easily controlled as hydrogen is only produced both the catalyst and reaction solution are in contact. Current limitations are that raw material costs are quite high, however plans are currently being put into place to recycle the sodium borohydride to make the process cheaper. Although the cost of the materials for this technology is considered high, the principal concern is over both the control and safety of such a solution. To be able to be considered a practical solution for HEVs, improvements must be made in the possible effects caused by the rise in temperatures, in order to prevent runaway reactions.

Carbon Nanotubes/Fibres research has been active in a number of institutions including: *DERA, Loughborough University, North-eastern University (USA) and Mannesmann (Germany)*. This technology is still only in the research stages, but so have the potential for very high storage densities. Carbon nanotubes do have a lower energy than that of nanofibres. The reaction between hydrogen and ethane/carbon monoxide over a finely divided catalyst bed produces carbon nanofibres. It is during the reaction that hydrogen is absorbed onto the catalyst. The exact carbon nanofibre structure is reliant upon the reactant gas and temperature of the catalyst. Through exposing carbon nanofibres to hydrogen at high pressures in the region of 120 bar, the absorption of hydrogen occurs.

By looking at the possibilities for the short to long term solution for energy storage systems in vehicles, it can be seen that there are many possible routes in which to move next. Current electrochemical battery options seem to be the optimum choice for current vehicles, but with improvements in the other technology types discussed, there seems as though there will be a shift in the approach to energy storage in the future.

6. HOW HYBRIDS WORK

6.1 Operating Features

6.1.1. Regenerative Braking

Regenerative braking is an advanced feature in an HEV which allows the electric motor to act as a generator in order to recapture energy that would once have been lost through heat dissipation and frictional losses.

a) Physical Brief

As any body, an HEV follows the rules of physics; equation 1:

$$F = m\ a \tag{1}$$

Where F is the force being applied, m is the mass (the vehicle mass in this case), and a is the acceleration of the vehicle. In simplified terms, the faster you want an object to accelerate, the more force you have to apply to it. These basic principals relate straight back to the configuration of an HEV.

Concentrating on the electric motor first, energy from the battery is applied to the coil windings within the electric motor. A magnetic force is then produced on the rotor of the motor, causing the production of torque on the output shaft. The generated torque is applied to the wheels of the vehicle via the coupled gears and shafts. The wheels then rotate; applying a force to the ground in the process. This force is due to the friction between both the wheel/s and the ground, enabling the vehicle to move along the surface.

b) Regenerative Braking Concept

The matter of frictional loss not only needs to be considered for conventional vehicles, but for HEVs as well. In conventional vehicles torque is generated in order to move the wheels to drive the vehicle on the road. During driving operations, friction is generated and losses occur. Through applying the brakes, the specially designed material in the brake pads, is able to handle the heat increases through friction applied to the drums and rotors preventing the wheel from turning. A conventional vehicle has frictional losses in order to move the vehicle, and uses friction in order to stop the vehicle. So the situation can be regard as a lose/lose situation.

When considering the frictional losses within a HEV, there are frictional losses all throughout the system. There is resistance between the electrons of the atoms moving in the wires between the electric motor and the battery, and through the electric motor itself. Produced magnetic fields incur friction in the metal laminations making up the magnetic circuit with the electric motor. There is mechanical friction between every mechanical moving part of the system, including gears, chains and bearings. As mentioned previously the by-product of friction is heat, and the higher the frictional force the greater the resultant heat. The consequence of the sum of the frictional losses, determines the overall efficiency of the vehicle.

The efficiency of HEVs is greater than that of conventional vehicles in the respect that HEVs can reclaim energy which would once have been lost through *regenerative braking*. The inertia of the vehicle is the fundamental factor in being able to reclaim the energy back into the batteries. Instead of using the full potential of the brakes of the vehicle, HEVs allow the linkages back to the electric motor such as the drive shafts, and gears transfer the torque from the wheels back to the electric motor shaft. Electric motors can transfer electrical energy into mechanical energy and back again, and in both case can be achieved very efficiently. The way in which electricity is reproduced is through the magnets on the shaft of the motor moving past the electric coils of the stator in the motor, passing the magnetic fields of the magnets through the coils. Electrical energy is then fed back into the battery, in turn charging up the hybrid battery pack.

There are two forms of *regenerative braking* which are *parallel regen* and *series regen*; this is not related to parallel and series configured HEVs (explained later). The forms are dependant on how many wheels are being used to reclaim the energy. The most common approach in vehicles is that the front wheels are the only wheels reclaiming energy. Energy is still lost in this case through the back wheels as before through minor heat dissipation, unless they are somehow connected back to the electric motor. The other key determinant factor is the battery *state-of-charge* (SOC) and how hard the energy is being driven back into the battery. Overall, the regenerative braking process is highly advantageous as it eliminates the need for a large, on-board electrical generating system, like the ones which have appeared on most parallel hybrid gasoline-electric drivetrains.

6.1.2 Planetary Gear Set

The *Battery Management System* (BMS) can be regarded as the *brains* of a hybrid system, but it is the planetary gear set which manages the physical interaction between the engine, electric motor and additional generator. The planetary gear set is a feature which appears only in parallel configured HEVs; it is not practical for use in a series configuration due to the coupling of the ICE and the electric motor/s in the parallel configured HEV. The planetary gear seamlessly harnesses and transmits power from the electric motor (high-speed), thus enabling a more compact and powerful motor. This results in a much longer life, fewer frictional losses and quieter driving.

6.1.3. Continuously Variable Transmission (CVT)

The *Continuously Variable Transmission* (CVT) further enhances the performance of a parallel configured HEV. A CVT offers the same potentials as a parallel HEV, offering increased fuel economy and minimising emissions in the process. The combination of the two is therefore a sensible and advantageous option to employ. Unlike conventional vehicles which have a fixed gear ratio typically offering 4 to 6 gear options, the CVT in an HEV allows for an infinite number of transmission gear ratios within the limits of the device. This is advantageous as it maximises the efficiency of the powertrain whilst allowing the driver to have a much smoother ride, thanks primarily to jolt-free acceleration. The main reasons behind moving from manual to CVT is so that the engine will always operate at its optimum regime and throttle-positions, whilst adapting to the varying road conditions and power demands. Currently, conventional vehicles do not make use of CVT, one reason for this is that its belt-driven orientation limits it application with vehicles of engine sizes over 1.2 litres; making a number of conventional vehicles incompatible with this transmission type. Other disadvantages include its large size and weight. However, developments are aiming to decrease these effects and make the

CVT a more viable means of transmission for all vehicle types in the future.

6.1.4. Integrated Motor Assist (IMA)

The *Integrated Motor Assist* (IMA) system owes much of its remarkable performance to the application of numerous technologies developed over the last four decades. *Honda* for example have used their knowledge in lean-burn combustion, low-emissions, variable valve timing, high efficiency motors, regenerative braking and nickel-metal hydride battery to their advantage in developing the IMA system for their *Insight* model. Their aim was to make the world's most fuel-efficient gasoline powered automobile. *Honda* optimised the performance of each of the technologies within their knowledge base to create an efficient, lightweight and compact hybrid drive system. The advantage of such a system is that it is easy for customers to use, and requires no changes in lifestyle either.

The key part of the IMA system is the *intelligent power unit* (IPU), which controls the flow of electricity to and from the motor, and controls the storage of the electrical energy in the battery pack. During deceleration and braking, the electric motor acts as a generator, in order to recharge the battery pack. More than 95 percent of the energy generated during the braking cycle is recovered for storage in the batteries.

The IMA in the *Honda Insight* boats an impressive 24 percent improvement in efficiency, which also combines with the fact that the *Insight* also meets California's stringent *Ultra-Low Emissions Vehicle* (ULEV) standard. Another advantage of the IMA system is it's capabilities for long-range driving. The *Insight* can travel in excess of 600 miles; all on a single tank of gasoline (10.6 gallon) [22].

6.2. Battery Management System (BMS)

The primary goal of the *Battery Management System* (BMS) is to increase the cell life of the batteries in a HEV. More commonly referred to as the *Electronic Control Unit* (ECU), it manages the power flow between the generator, battery and the electric motor. By keeping a constant monitor over various driving conditions, the BMS allows the transmission to gain optimal power and fuel consumption from the powertrain. The BMS manages the interaction between the battery and electric motor, optimising the movements between both in the process [23].

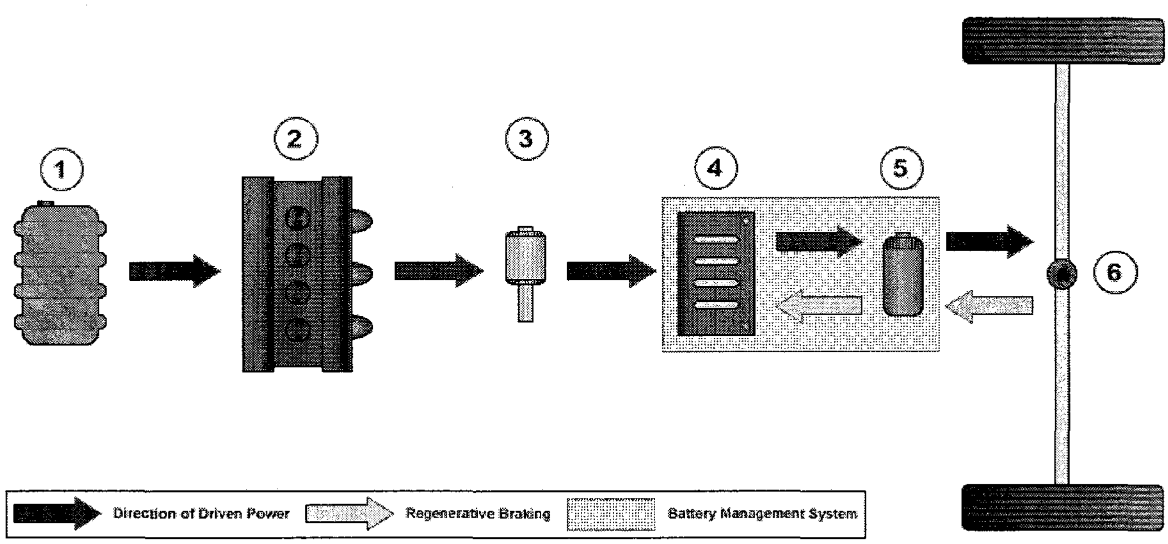

Figure 3: Series Configured HEV

7. CONFIGURATIONS

7.1. Series HEV

In a series configuration HEV the engine never directly powers the vehicle. The concept of the engine is to initially charge a large battery pack, which in turn will power the electric motor in order to provide power to drive the wheels with or without the transmission. Observing the components of the series configured HEV the list featured in figure 3 are as follows: component 1 is the fuel tank, 2 is the ICE, 3 the generator (optional in a parallel configured HEV), 4 the battery, 5 the electric motor (can also operate as a generator when none is present) and 6 the transmission.

There are a number of disadvantages however, associated with the series configuration. The series configuration requires an alternator-rectifier, which is not needed in a parallel configuration. The alternator-rectifier converts the AC electrical power into a form which is suitable for use in the electric motor. The *total* system efficiency is reduced due to the conversion of mechanical to electrical power and back to be stored when converted in order to drive the wheels. There have been a lot of simulation efforts gone on with series configured HEVs in order to fully optimise this configuration of the drivetrain [24]. Improvements with this configuration make it a viable configuration to be considered for future HEV models.

TABLE II
DRIVING RANGES FOR A SELECTION OF CURRENT HEVS

Model	Max. Range (km) (City)	Max. Range (km) (Motorway)
Honda Insight (Manual)	1,033	1,150
Honda Insight (CVT)	960	950
Honda Civic (Manual)	970	1,075
Honda Civic (CVT)	1,033	1,150
Toyota Prius	990	856

Source: "*Technology Snapshot*", by Thomas J. Gross, An introduction by the U.S. Department of Energy to commercially available vehicle technology, United States Department of Energy, Energy Efficiency and Renewable Energy.

The electronic controls monitor the electric motor to ensure the accelerating up to passing speeds is both quick and smooth. As previously discussed, the operation of *regenerative braking* is shown by the light grey arrows in figure 3. The direction of driven force is also shown as the darker selection of arrows. An advantage of a series configured HEV is that it is possible to run the ICE at a constant speed whilst still being able to share its electrical output to charge the batteries and supply the power to the wheels; minimising the emissions of the vehicle.

7.2. Parallel HEV

The engine in a parallel configuration connects straight to the transmission as does the electric motor. Like the series configured HEV it has a small ICE that works in parallel with an electric motor. During less intensive power cycles the parallel hybrid can utilise the engine in charging the battery pack, such as when cruising at freeway speeds. Parallel configured HEVs have the ability to turn off the engine and run purely off the electric motor for short urban driving. Thus, behaving as a fully functional

EV, and becoming virtually emissions free during these periods. This can not be achieved with the series configuration as there is only a direct link from the ICE to the transmission via the electric motor. The range of a parallel configured HEV is over 640 km, which is the limited for a series configured HEV. From table II it can be seen that the driving range has been well in excess of this figure in the first three mechanical energy the system is far more efficient than the series HEV, which requires two.

The one big disadvantage with a parallel configured HEV however, is that the ICE can only be mounted in a few very well defined positions in order to enable the drive to be mechanically coupled with the powertrain. This also affects other ICE

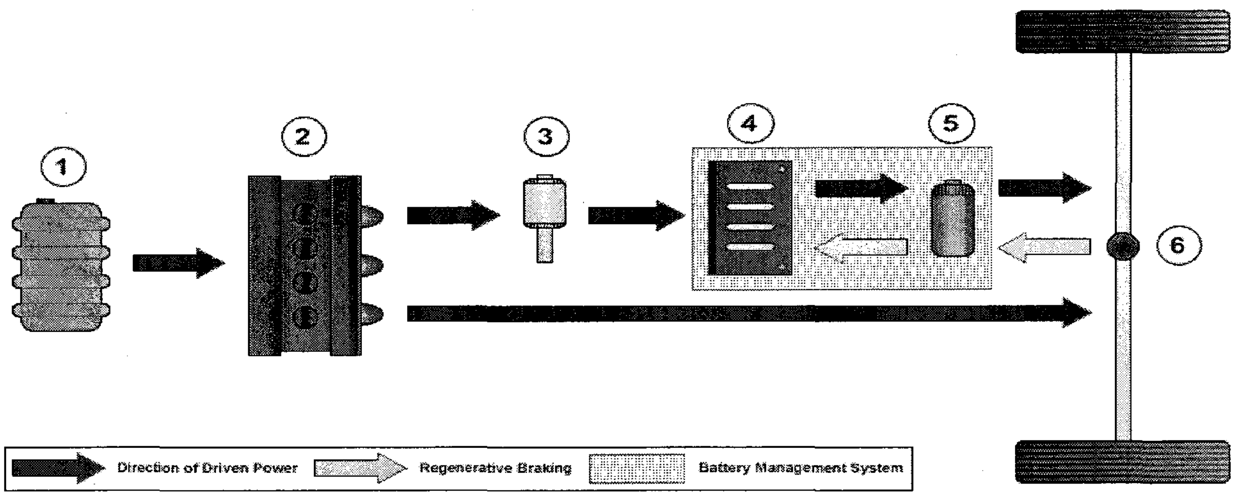

Figure 4: Parallel Configured HEV

HEV models on the market; satisfying the majority of all journeys. Figure 4 has the same list of components as the series configuration, with the addition of the ICE being able to operate the transmission directly.

The mechanical output from the ICE in a parallel configured HEV can be controlled by a *continuously variable transmission* (CVT) with a clutch and a three-way gearbox; a number of studies of which have looked into optimising and developing this process [25]. The three-way gearbox operates in such a way that it is capable of transmitting mechanical power in either direction in order for the disengagement of the clutch between the CVT and the gearbox to allow for fully regenerated power to be directly stored in the battery by passing through the electric motor/generator.

There are a few advantages a parallel configured system has over a series configuration. Firstly, unless the battery is low of charge the engine noise is kept to a bare minimum because the engine is only operating when the vehicle is moving. As there is only one conversion between electrical and vehicles, but it is far less restrictive than for parallel HEVs. Also, since the engine speed varies more within a parallel configuration the emissions will be slightly higher than what you would have in a series configured arrangement.

7.3. Start/Stop Hybrids

A *Start/Stop* hybrid can not be considered as a true hybrid vehicle, since the electricity from the battery packs is not used to propel the vehicle. It is a useful transitional technology type which has helped to boost energy-saving building blocks for hybrid vehicles which have followed on from this. *Start/Stop* hybrids conserve energy by shutting off the ICE during rest periods. The ICE will then restart when the driver pushes the pedal again to go forward.

During the initial driving phase the ICE only starts when the vehicles has begun to move from a rested state. Whilst the vehicle is pulling out the electric motor/generator uses electricity from the battery to instantly start the ICE. The ICE is the only power source of the vehicle.

During the braking phase of the vehicle, the *start/stop* vehicle uses a combination of both *regenerative* and *conventional friction braking* in order to slow the vehicle. These features are also offered by full hybrids, which is why some would consider the *start/stop* option to be an HEV.

7.4. Summary

The shift from traditional ICE vehicles towards the future prospect of fuel-cell vehicles is illustrated in figure 5. It is important to understand that the majority of the vehicles have already been a success in the world market, and the shift in propulsion sources each time, have made the vehicles more efficient and environmentally friendly. It is important to maintain this shift within the automotive industry, and inspire other industries to follow in the same line to provide a cleaner future for the planet.

8. HEV MODELS

8.1. Honda Insight

The *Honda Insight* was the first HEV to be sold in the US; released in December 1999. The *Honda Insight* is a parallel hybrid which combines an advanced powertrain with light-weight materials, helping it to be aerodynamic and ultra-low emissions. The core of the Honda Insight system is *Honda's Integrated Motor Assist* (IMA™), which combines a 1.0-litre, 3-cylinder engine and an ultra-thin permanent magnet electric motor in order to achieve efficiency. The *Honda Insight* can achieve 68 mpg in the city and 61 mpg on the motorway [26]. Other reports regard these figures as questionable as other suggestions state the vehicle can only achieved 47 mpg [27]. It is important to compare the differences in the fuel economy estimates between various sources, as this is one of the key selling points for HEVs. With such differences in estimated values, it puts into question whether the measuring process is legitimate or not. This needs to be considered in order for HEVs to gain a stronger market share than they already possess.

The *Honda Insight* sold nearly 5,000 models within its first year. These sales are the second lowest figures among the 14 models of *Honda*, which are currently available in the US, which is expected due to the overall market share HEVs currently have in the market in general. *Honda's* best selling car being the Accord (38,000 sales in March 2000). The driving conditions of the *Insight* are very similar to any comparable conventional car, but you must remain in gear whilst slowing down in order to recover energy. The brake pads

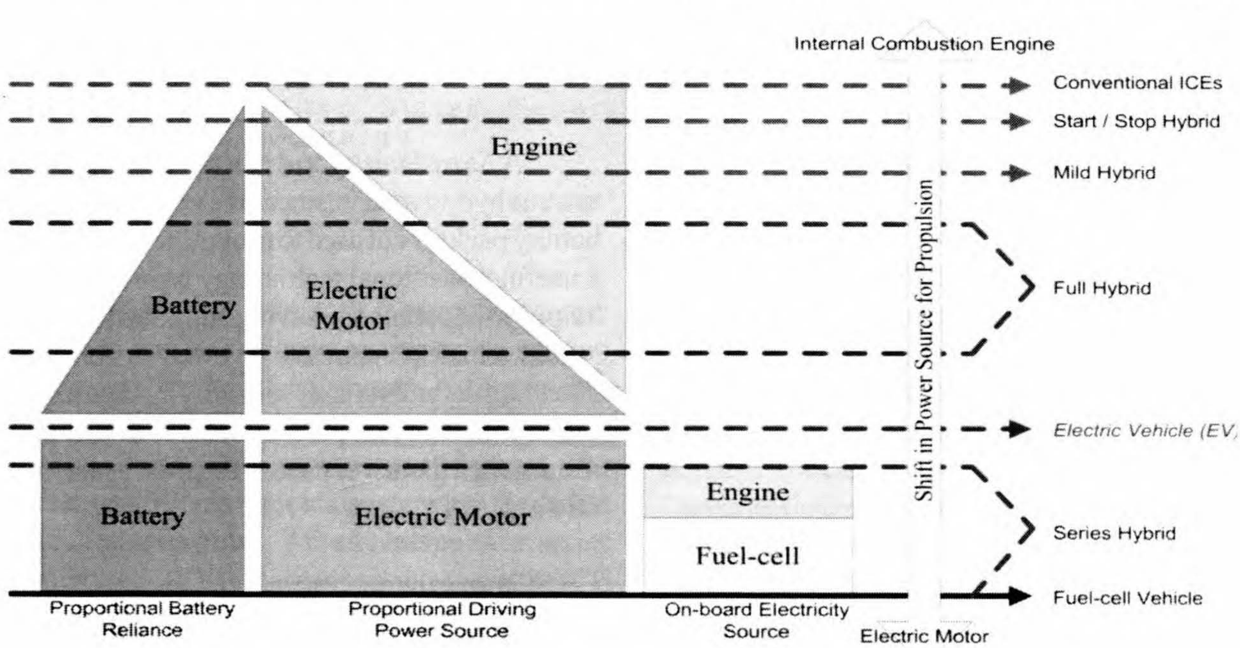

Figure 5: Hybrid Types and Configurations

TABLE III
CURRENT AND FUTURE HEVs

Vehicle Type	Manufacturer	Model	Release / Expected Release Date	Engine Horsepower	Electric Motor Horsepower	Net Horsepower
Compact / Sedan	*Honda*	*Insight*	2000	65 hp	13 hp	71 hp
	Toyota	*Prius*	2000	76 hp	67 hp	110 hp
	Honda	*Civic*	2003	85 hp	13 hp	93 hp
	Honda	*Accord*	2005	240 hp	16 hp	255 hp
	Lexus	*GS 450h*	2006	–	–	–
	Ford	*Futura*	2006	–	–	–
	Nissan	*Altima*	2007	–	–	–
	Chevrolet	*Malibu*	2007	–	–	–
SUVs / Minivans	*Ford*	*Escape*	2004	133 hp	94 hp	155 hp
	Lexus	*RX 400h*	2005	211 hp	167 and 68 hp	268 hp
	Toyota	*Highlander*	2005	–	–	270 hp
	Mercury	*Mariner*	2005	–	–	155 hp
	Saturn	*VUE*	2006	–	–	–
	Chevrolet	*Tahoe*	2007	–	–	–
	Dodge	*Durango*	2007	–	–	–
	GMC	*Yukon*	2007	–	–	–
	Toyota	*Sienna Minivan*	2007	–	–	–
	Audi	*Q7*	2008	350 hp	44 hp	-
	Porsche	*Cayenne*	2008	-	-	-
	BMW	*X3*	-	-	-	-

Source: Hybrid Electric Vehicles - A General Review, John E W Poxon 2005.

will last longer than those of a comparable conventional vehicle; due primarily to the onboard *regenerative braking*.

The *Insight* has an 8 year warranty on the majority of the powertrain, and a 3 year warranty on the rest of the car. Both the motors and the batteries of the Insight require no maintenance over the entire life of the vehicle. The current price of which you can purchase a *Honda Insight is* $19,085 (15,705 €). The *Honda Insight* is not currently available in Europe, it is only currently selling in the US and Japan.

8.2. Honda Civic

The *Honda Civic Hybrid* was first released in the US in March 2002. The *Honda Insight* was the first vehicle to introduce *Honda's Integrated Motor Assist* (IMA™) system. The IMA system is the motor generator system which powers the vehicle. *Honda* used the lessons learnt in HEV control and strategy from the *Insight*, and improved them for their *Civic* model. The *Honda Civic*, a parallel HEV incorporates the second generation of IMA. The new IMA system combines a 1.3-litre, 4-cylinder i-DSI (intelligent Dual and Sequential Ignition) gasoline engine with a 10 kW ultra-thin permanent magnet electric motor.

During 2003 the *Honda Civic Hybrid* set consecutive records during March, April and May, and sales during 2003 were up by nearly 20 percent compared to those figures obtained during 2002 through to the end of May. Work has gone into the further development of the powertrain for the *Honda Civic*, by improving the engine; with increased motor torque, higher efficiency and improved CVT [28].

The *Honda Civic* hosts a computer control system which manages the power of the motor, charging system and *nickel metal hydride* (NiMH) batteries. The i-DSI gasoline engine is resourceful due to its lean-burning combustion technology with two spark plugs per cylinder. The cylinder idling system helps to improve the *regenerative braking* capabilities of the vehicle; whilst idling or decelerating; more energy is recaptured by the electric motor and stored in the batteries.

The *Honda Civic* boosts a 40 percent better fuel economy than that of a comparable *Civic Sedan*; achieving 51 mpg in the city and 46 mpg on the motorway. The vehicle meets the *ultra-low emissions vehicle* (ULEV) standard, by keeping NO_x below required levels. To keep NO_x emissions within the ULEV, *Honda* developed a NO_x absorptive catalytic converter which used a mixture of platinum and other metals to attract the NO_x molecules to its surface during lean combustion. The stored NO_x is converted into harmless nitrogen and water by regenerating the catalyst on a regular basis by changing the engine fuel strategy to a slightly richer run (more fuel and less air). You can drive the *Civic Hybrid* for up to 1,033 km (as shown in *table II*) on a single tank of gas; generating in the process 50-80 percent fewer emissions compared to that of a standard five-passenger car. The price at which you can buy a *Honda Civic* stands at roughly 22,200€.

8.3. Toyota Prius

The Toyota Prius was in fact the first mass produced HEV in the world. During 2005, Toyota has currently imported 1,000 Prius models per month to the US from Japan, and sales are at their highest in Southern California and the Pacific Northwest. The main objective of the inclusion of the Prius was to reduce exhaust emissions in urban areas, and in order for Toyota to accomplish this they designed and created a parallel hybrid powertrain. It boasts some of the benefits that would be achieved from both a series and a parallel hybrid; named aptly the Toyota Hybrid System (THS) [29].

The Prius uses a power split device which allows the engine to be at its most efficient load and speed range for the majority of the time. The Power Split Device (PSD) is regarded as the heart of the Prius, and allows the car to operate with the benefits of either a series or parallel hybrid. The PSD is can also be reference as the CVT, however it is not the usual type (Cone and Belt) found in traditional vehicles and other HEVs. Alternatively, this CVT is referred to as the planetary type, due to the orbital movements of the components within it.

Away from the purely hybrid benefits, the Toyota Prius is considered even more environmentally friendly as it is made from 90 percent recyclable materials. The ICE and the electric motor are connected to the wheels by the same transmission. The Prius can achieve 52 mpg in the city, 45 mpg on the highways and can go from 0-60 mph in 14 seconds. However, Consumer reports magazine say that under testing the Toyota Prius it achieved 41 mpg [30]. Again, stressing the fact of the variability in such estimations. The current sales price of the Toyota Prius is 25,912€.

8.4. Current and Future Models

The important thing to consider for the latest HEV models into the market is the shift towards the premium range of vehicles (Table III). The inclusion of the Lexus RX 400h at the beginning of 2005 has made it the world's first luxury hybrid vehicle. The Lexus RX 400h will further go towards breaking the EV minded vehicle buyers by offering a substantial 268 hp. With increasing movements towards the premium end of the market, the commercial success of HEVs and 4x4s vehicles as a whole is sure to grow.

In fact, even the European car manufacturers such as Audi, BMW or Porsche who were reluctant to develop HEVs, will soon begin to offer this technology in some new models. Volkswagen will also develop a HEV for the Chinese market before the next Olympic Games (2008) which will be celebrated in Beijing.

These new planned models will include novel solutions such as the supercapacitor technology in the BMW X3 hybrid. Also, the integration of solar cells into the open sky system (the SUV's large-format glass sunroof) in the new Audi Q7 hybrid in order to add another source of energy.

9. HEV MARKET STATUS

The objective of this section is to describe the current market status of the European, US and Japanese markets for HEVs. Figure 6 displays graphical representations of the predictions for each market in order to illustrate the following trends.

9.1. European Market

Due to the healthy diesel tradition and the permissive policies in emission legislation in Europe, HEV sales have not been as substantial as those currently in the US. Another reason for this is that Europeans are not as excepting for hybrids as the US have currently been. Some Europeans have refused to believe in the hype behind this technology; however this is due to change over the next number of years. For these reasons the European market will need more time in order to get the aggressive incline like the Japanese and US markets have already witnessed (figure 6). Toyota does hope to sell between 15,000 and 20,000 Prius' in 2005, aiming to capture 0.11% of the European market.

9.2. USA Market

Since the introduction of hybrid cars in the US market in 1999, sales have had a rapid increase, as shown in figure 6. These sales have grown by an average annual rate of 88.6% from 2000 to 2003, according to *Michigan-based R.L. Polk & Co.* In contrast, according to *ABI Research*, in 2006 HEV sales will represent 10% of the 2 million midsize vehicles sold annually in the US market [31]. Undoubting, looking at figure 6 it is clear to see that this market along with the Japanese has the most potential riding on it.

9.3. Japanese Market

In 2003, HEVs were position third in Japan's *Automotive Emerging Technologies Study* [32], based on consumer familiarity, interest and purchase intent. The two features which came in front of HEVs were navigation and night vision systems. However, the HEV technology leaped to first position within the same study the following year. This fact illustrates the importance that the main Japanese car manufacturers (*Honda* and *Toyota*) have in hybrid vehicles becoming a significant share of the worldwide automotive industry. The resourceful commitment by both *Honda* and *Toyota* has had positive affects on the final Japanese customers, as illustrated in figure 6. *Toyota* has even begun to suggest in many congresses that

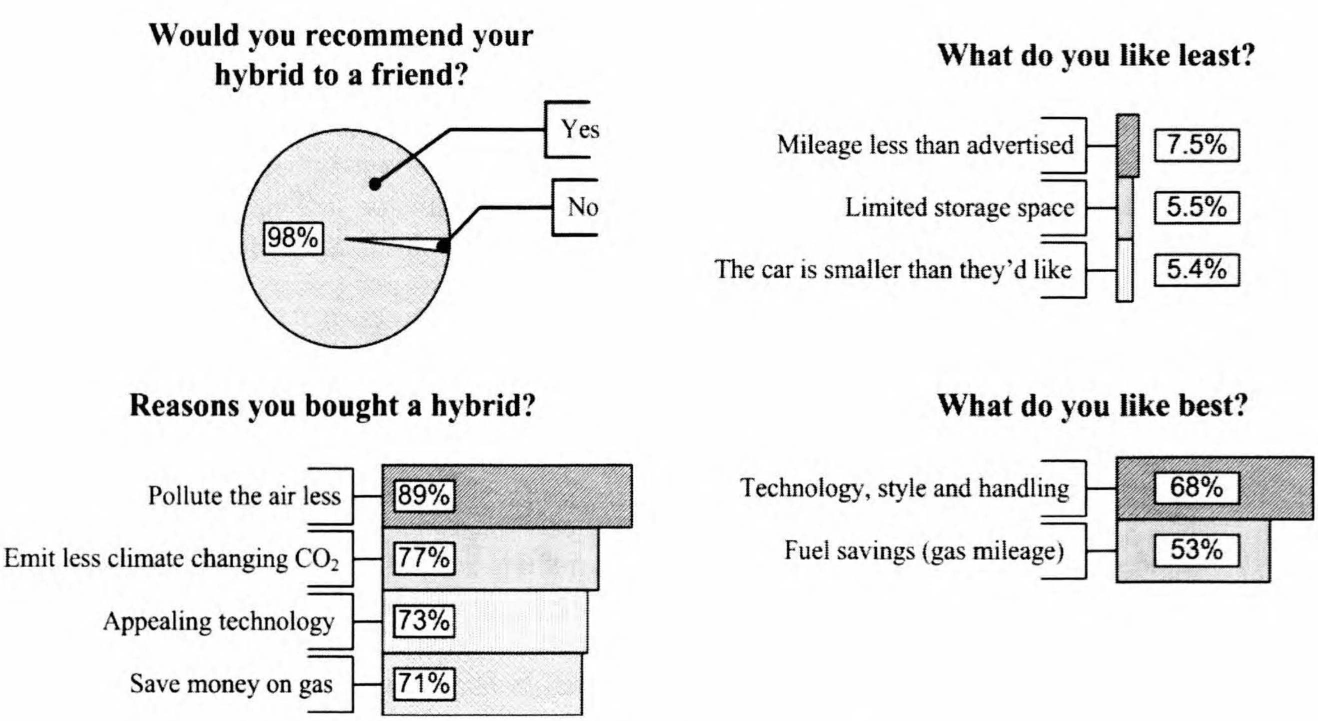

Figure 7: Hybrid Drivers Survey (Source: Oregon Environmental Council 2003)

theforecast of HEVs will be a 90% share of the Japanese market in 2010.

10.BUYING ISSUES - HYBRIDS VS. DIESELS

When a customer goes out to buy a new car, there are a number of factors which can determine which vehicle if any they will buy. Customers have differing priorities which could be based on their country's culture, past experiences, costs, and/or his/her own personal preferences. Many customers though have become more aware and are starting to consider alternative technologies as apposed to the more conventional ICEs. For a number of reasons customers are considering alternatives such as HEVs and diesel vehicles. The main issues taken into account when considering the purchase of such vehicles are analysed in the following section.

Although Biodiesel is not a reality yet, the current diesel technology is the main alternative to hybrid technology. Diesels have the advantage of being fully established and are currently of lower cost than HEVs. Due to these reasons, the arguments are going to be presented as a comparison between hybrids and diesels.

Four key factors regarded in this paper for buying an HEV are; *cost*, *driver surveys*, *benefits legislation* and *image*. The last issue is discussed within the subsection *environmental concerns* presented in the third section. Notwithstanding, it will be considered from another point of view.

10.1. Costs

One of the most important factors when a customer wishes to buy a car is the associated cost. Economics may be the biggest obstacle in accepting hybrids. *Table IV* illustrates an estimation of the added retail price for a variety of HEV configurations.

At a first glance it can seem very high price, especially if this cost is compared with the diesel costs (*Table V*). However, according to the consulted sources, and for the European and US market, the diesel technology may rise over the next few years due to the increased manufacturing costs and the development of costlier pollution control systems [33]. This estimation is based on the most likely future legislation which will establish a more restricted pollution limits, and the fact that diesels will aim to have lower emissions than HEVs with the

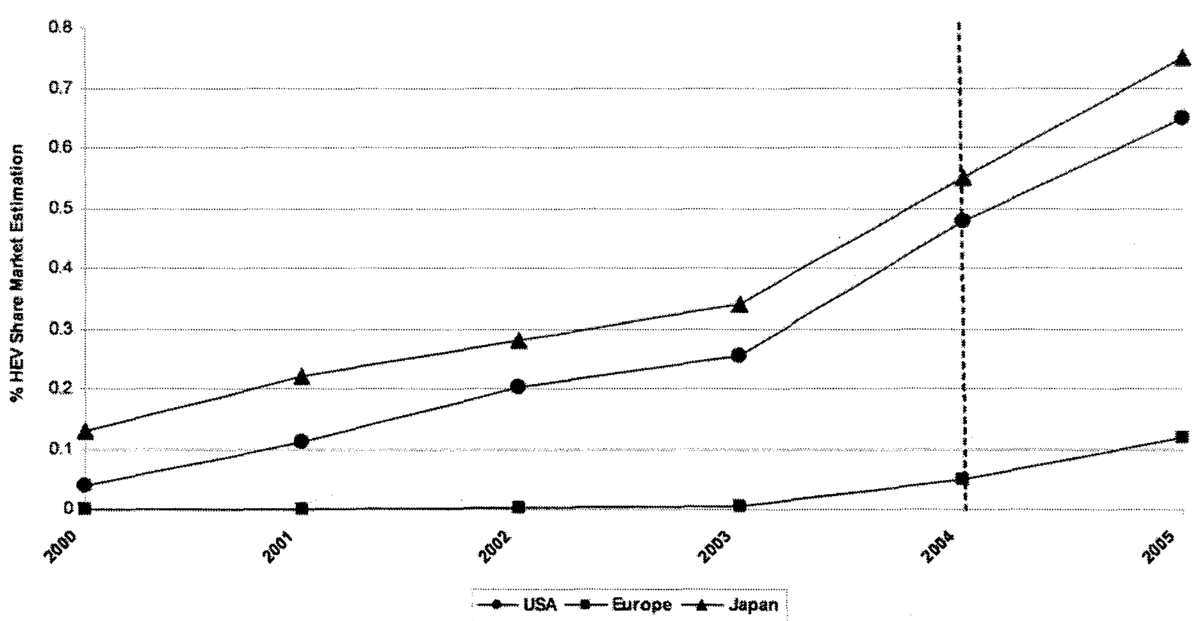

Figure 6: *HEV share and market estimation*

inclusion and development of biodiesel. Over the life time of a HEV the customer will save money on fuel expenditure, which help top balance out the initial offset of costs concerned and offer incentives into the purchase of HEVs. For example, one can claim $2,000 if he buys a hybrid car certified by the IRS (for example: *Toyota Prius*, *Honda Insight* and *Honda Civic Hybrid*) during 2004 and 2005 in USA; this deduction is going to drop to $500 in 2006 [34]. On top of the offered incentives, there are many states which offer additional incentives to this state deduction [35]. In [36], it is possible to check the different incentives in Europe. In the particular, in the Spanish case, the subvention is reduced to *Castilla Leon* where it is able to get a maximum reduction of 4,800.

TABLE V
ESTIMATED ADDED RETAIL PRICE FOR DIESEL ENGINES

	Small Cars	Midsize & Large Cars
2005	$1,750	$2,300
2008	$2,280	$2,925

Source: *"Future Potential of Hybrid and Diesel Powertrains in the US Light-Duty Vehicle Market"*, by David L. Greene, K.G. Duleep, and Walter McManus, Report to Department of Energy, July 2004.

Concluding, the US is strongly gambling a number of their resources in the hybrid technology, which is undoubtedly benefiting the rise in sales, along with the overall potential of the market. Whereas, European countries do not have a common benefit policy regarding this issue, and as far, have provoked a sales deadlock in favour of the diesel market.

10.2. Hybrid Drivers Surveys

Another important factor when evaluating the potential buying of an HEV is the opinion of the current hybrid drivers. These kinds of statistics show the grade of happiness of the customer, offering potential customers the chance to know the weak and strong points. The *Oregon Environmental Council* (OEC) did a survey in late 2002 and early 2003, expecting to receive the feedback of 596 hybrid owners [37]. The results that they published are provided in figure 7. The results from the Oregon survey could represent the general view of HEVs in the US; as there is not a substantial difference with the views of drivers in other states within the US.

At a first look *fuel saving* could be the most popular answer to the question «***Reasons you bought a hybrid?***». The truth is that it obtained an impressive fourth position with a vote of 71 percent. According to this survey, *pollute the air less, emit less climate-changing CO_2, appealing technology* are considered the most valuable advantages for hybrid owners. Therefore, the environmental motivation is the unique hybrid selling point. This in fact is a marketing issue rather than a technical one as the increase in CO_2 emissions is equivalent to the decrease in fuel consumption. ($CO_2\uparrow \Rightarrow kml^{-1}\downarrow$).

10.3. Image

The image or background perception that a customer has of a prospective product is an important factor to take into account. In fact, the companies are investing more and more into improving the advertised image material.

Diesels have in the past and still slightly today, suffer several image problems. As well as the noisily, underpowered and smell relative to gasoline vehicles, the pollution is presented as the most unpopular. An example of how significant the pollution problem still is for current diesel will be provided; According to EPA's Air Pollution Scale (1 to 10 being the 10 lowest pollution), the diesel *Volkswagen Golf* 1.9 (105 CV) obtains 1 and the gasoline 2.0 version is rated 6. However, on the same scale, *Toyota Prius* earned 9.5 [38].

Although these problems have been improved over the last number of years, there are many owners of gasoline vehicles who still believe that about diesels. Also, important markets such as the

US do not accept this technology for historical issues.

In the hybrid case are some image barriers which are due to the lack of knowledge. The two main objections supposedly inferior to gasoline vehicles are reliability and acceleration.

With respect to acceleration, it is possible to check that the used time to get 100 Km/h in a *Toyota Prius* is 10.9 sec whereas the *Seat Leon 1.9 Tdi* (110 CV) is 10.7 sec; less than 2% of a difference. Also, in order to illustrate the research invested in this technology, *Toyota* is evaluating the possibility to produce a *Sport Prius* which accelerates from 0 to 100 Km/h in 8.7 sec.

On the other hand, the warranty provided by *Toyota* on the *Prius* is 8 years for its hybrid system. This fact shows the trust in the hybrid technology.

Another important detail which is hard to ignore is the potential positive influence of so many celebrities jumping on the hybrid bandwagon. *Cameron Diaz*, *Leonardo DiCaprio* and *Jack Nicholson* are just a few who have expressed an interest in HEVs. In fact, many *Hollywood* stars used the *Toyota Prius* instead of the classical limousine at the last Oscar's night. Other reference, in words of *Matt Petersen*, president of *Global Green USA*: «*These celebrities probably don't worry about saving money at the gas pump, so their choice to ride in a Prius clearly demonstrates their concern about the sustainability of our environment*».

11.FUTURE TRENDS

According to a major part of the consulted references, the hybrid fuel cells are the expected energy for the future. In words of *Rick Wagoner*, chairman of *General Motors*: «*The hydrogen fuel cell is the ultimate answer for eliminating the automobile from the environmental equation*», [39]. However, the truth is that at the moment is an incipient technology. The difficult storage, the low autonomy and the required energy in order to get the liquid hydrogen state still make very expensive the use of this technology. Currently it is less environmentally friendly due to the energy origin necessary to liquid and to do electrolysis process in order to get the final hydrogen fuel [40].

Therefore the possible technologies usable in a near future are two: biodiesels and HEV. HEV is already explained extensively. But, what is the definition of biodiesel? Biodiesel *is the chemical product of a vegetable oil or animal fat with an alcohol such as methanol or ethanol in the*

TABLE IV
ADDED RETAIL PRICE FOR HYBRID SYSTEMS

Hybrid System	Small Cars	Midsize & Large Cars
Stop/Start	$600	$640
ISAD	$1,250	$1,385
IMA	$1,620	$1,790
Full Hybrid	$3,320	$3,920

Source: "*Future Potential of Hybrid and Diesel Powertrains in the US Light-Duty Vehicle Market*", by David L. Greene, K.G. Duleep, and Walter McManus, Report to Department of Energy, July 2004.

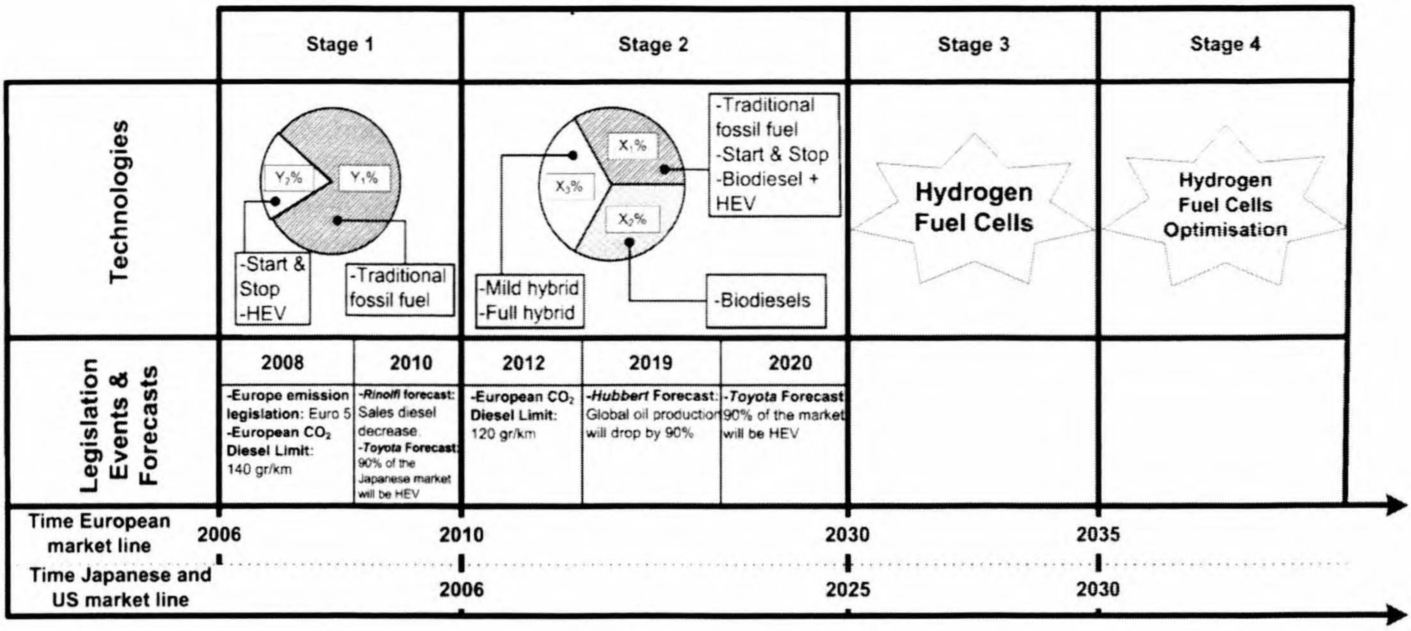

Figure 8: *Fuel Future Trends Estimation based on important forecasts.*

presence of a catalyst to yield mono-alkyl esters and glycerin, which is removed [41]. There are some arguments which favour the use of biodiesel, for example: it is the *Volkswagen* option and it is starting to be used in a small selection of gas petrol stations around the world. However, the major disadvantage of biodiesel is still the high production costs. Also, the potential increased use of biodiesel requires cautious reflection of all environmental impacts. While positive impacts such as decrease in fossil CO_2 emissions at the combustion stage are evident, the indirect impacts such as from fertilizer production, agriculture, and fuel processing are more complex to analyse [42].

Another parameter in order to know HEV future trends are car manufacturer's opinions about the different requirements that they demand of the batteries. *Ford*, *Jaguar*, *Land Rover* and *Volvo* managers have expressed the improbable introduction of a 42V supply due to it is not affordable as a short-term solution for price-sensitive mainstream passenger cars [43]. In the short-term, according to [43] and [33], the 12V systems such as Start/Stop will be introduced in the short-term European car market. However, the full hybrid configuration is strongly supported by the Japanese and US markets [44].

Figure 8 shows the proposed automotive technologies estimations based on future legislation and forecasts [33, 43-46]. It can be distinguished that there are two time lines in figure 8; one for the European market and other for the US and Japanese market. The first stage is just valid for the European market where 12V systems such as Start/Stop and traditional vehicles will live together [33]. This is a transitional stage necessary for the European market due to a clear common legislation absence in favour of full hybrid or biodiesels for the moment. In fact, the systems with 12V which save some petrol and emissions are the best option for a number of car manufacturers [43]. However, these systems will represent a minority ($Y_1\% >> Y_2\%$).

The second stage will start around the year 2010 for the European market and the next years for the US and Japanese market. HEV and biodiesel will increase their percentages on the market ($X_1\% \uparrow$ and $X_2\% \uparrow$) in this stage appreciably due to the restrictive legislation in the European market (e.g. Euro 5 [45-46]) and the benefits subventions and image issues in the US market. In fact, *Toyota* forecasts that HEVs will represent a 90% share of the overall market and it hosts of deal of certainty, taking into account *Hubbert's* prevision for 2019 [1]. However, the biodiesels in Europe will be more popular than the HEV ($X_2\% > X_1\%$) in contrast with US and Japanese market which will have the opposite occurrence ($X_1\% > X_2\%$). At the end of stage 2 (around 2030) the traditional fossil fuel cars will be displaced in benefit of cleaner and more efficient technologies. Even *Rinolfi*, common rail's father, has forecasted a cost boost in diesels vehicles in 2010, supporting undoubtedly the increase of HEV sales [33].

The third stage represents the triumph of hydrogen fuel cells. This technology will be used in order to mitigate the petrol shortage. However, as any incipient technology it will need time to optimise it's process. In fact, its whole potential could be accomplished within a few years (stage 4).

12.CONCLUSIONS

In conclusion it can be seen that the growth in market potential of HEVs is strongly influenced by the movements of legislation. Therefore, benefits and stringent emission legislation is common in areas where HEVs have been successful. The US and the European markets are two important automotive markets which have been analysed in order to demonstrate the current success of HEVs.

The US market is currently suffering strong rises in fuel prices, and as a reference rose by almost 40% within the first quarter of 2004. Geopolitics during this period has also led to the US being less dependant on Middle Eastern oil reserves. There are two alternative means as discussed which can be considered as solutions to these current scenarios; HEVs or diesel vehicles. As shown by movements in benefit legislation and the growing restrictions in vehicular CO_2 emissions primarily, HEVs have been the more dominant choice. Currently, diesel vehicle sales in the US represent approximately 1 to 2 percent of the market share; mainly due to the historical issues of the technology. For this reason, the introduction of more stringent emission legislation against diesel vehicles is extremely important for these manufacturers (mainly the European *VAG* Group). However, after the US's resignation from the *Kyoto* agreement they can now project a *green image* through the support of HEVs with benefit legislation. This can be exploited as a new market opportunity by their car manufacturers. In fact, *General Motors* are currently the third biggest HEV manufacturer in the world behind *Toyota* and *Honda*.

In Europe though, diesel technologies have been favourably stronger than in the US, which is mainly due to the appropriate tax conditions and the healthier acceptance of the technology. The diesel market within Europe has continued to remain healthy as high fuel prices have provoked a number of benefit legislation attempts during the eighties and nineties. In fact, over the last year 46 percent of new car registrations in Europe were diesel; this figure stands at 60 percent in the Spanish market [48]. This situation could ultimately change in Europe if more stringent emissions legislation were to be introduced, which could be the case when the *Euro-5* is introduced in October 2009. Currently, there are no countries in the *European Union* (EU) which offer uniform rebates on the purchases of HEVs, unlike the US. Clearly, with increased awareness and further governmental movements, HEV sales in Europe are sure to increase; as has already occurred in the US. If legislation were to remain unchanged in Europe then there would still be an increase in HEV sales, just at a slower rate than those currently in the US; these would however continue to rise as the technology became more established. The marketing and fashions associated within this technology area along with the growing concern of global warming are other factors which are influential regardless of legislation; these factors alone would increase the sales potential of HEVs.

Concluding, HEVs will have a definite stronghold in the future of automotive development, due to the flexibility of the technology. The current configuration of HEVs (electric motor and ICE) is strongly influenced by legislation, but future hybrid technologies could work with biodiesels or even fuel-cells. The generated braking energy is one clear example of green power which can be taken advantage of when the current driving conditions are optimised; regardless of future choices of energy storage devices.

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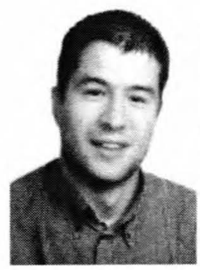
AUTHORS



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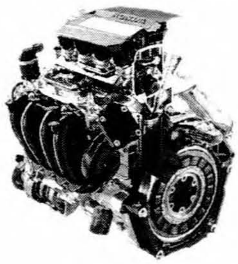
He is a member of the Technology & Information Group (TIG). This is a research team based at the University Of Warwick in the Warwick Manufacturing Group's (WMG) International Manufacturing Centre (IMC). For the last 16 years they have been working closely with the automotive industry on a number of technology issues.

DO HYBRID ELECTRIC VEHICLES REALLY WORK?



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ABSTRACT

Most articles about hybrid vehicles concentrate on the benefits, this paper introduces the limitations of hybrid vehicles. These include effects on the vehicle electrical system, extra vehicle weight and the requirement for battery monitoring. To achieve this, the paper briefly describes how a hybrid vehicle functions and then examines the output of a hybrid vehicle software simulator (ADVISOR 2002). A comparison of hybrids against standard cars is also made. Suggestions for future research is also made.

Index Terms—Hybrid Vehicles, Batteries, SOC, SOH, Drive Cycle, ECE15, EUDC, Hybrids vs. Diesels.

1.INTRODUCTION

The reduction and cleaning up of vehicle emission has been ongoing for many years, partly driven by increasingly stringent environmental legislation. Engineers have been steadily improving vehicle emissions by introducing technologies such as fuel injection to improve engine efficiency and catalytic converters to remove unwanted gases. A new technology is currently being introduced to further reduce emissions. This new technology is called «Hybrid Electric» This paper examines how «Hybrid Electric» technology could be used to reduce emissions further. Potential problems with introducing hybrid technology are also discussed. The methods by which emissions can be reduced are first discussed. Then the performance of a hybrid electric vehicle is discussed via a software simulation and finally a comparison with other vehicles on the market is made to highlight the benefits for vehicle buyers and users.

2.METHODS TO REDUCE EMISSIONS

Vehicle manufacturers have been set ever more demanding vehicle emission legislation to help reduce global emissions of CO_2. Hybrid Electric is one of the new technologies that can help to lower emissions. Emissions are caused by the burning of fuels to release energy. Therefore energy usage must be reduced; this can be achieved in a vehicle by the following methods:

- Reduce weight
- Improve engine efficiency
- Reduce energy losses

Each of these methods will now be discussed further in the sections below.

3. WEIGHT REDUCTION

Basic physics shows that the kinetic energy of a body is related to it's mass (essentially it's weight). The following equations shows this relationship.

$$E = \tfrac{1}{2} \cdot m \cdot v^2$$

Where E = kinetic energy, m = mass, v = velocity

Therefore reducing the weight of the vehicle will reduce the energy required to move the vehicle and thus reduce emissions.

Hybrids have two propulsion systems the Internal Combustion Engine (ICE) and the electric motor. The extra propulsion system will add weight to the vehicle. The additional components that are required are an electric motor / generator, a battery or storage device, control electronics and thermal management systems for the battery, motor and power electronics.

Therefore some of the gains from the hybrid technology are lost through increased weight. However as hybrids have two methods of propulsion the ICE could be downsized (made smaller) to save weight and hence compensate for the weight of the additional components.

3.1. Electromechanical Systems

A trend in the automotive design is to replace mechanical systems with electric / electromechanical systems. Table I shows examples of these electromechanical systems. These systems can improve comfort, reliability and efficiency.

Ideally a hybrid vehicle could be able to move with the engine turned off, however some systems such as power steering, brakes and air conditioning are currently powered directly by the engine. The simplest method to solve this problem is to add an electric motor to drive these components, however this adds weight. The best solution is to continue the trend and replace the system with an electrically powered electromechanical version; this would allow the system to function when the engine is turned off.

Mechanical System	Equivalent Electromechanical System
Belt driven cooling fan	Electric Fan
Wind up Windows	Electric Windows
Manual Seat Adjust	Electric Seats
Carburettor	Fuel Injection
Hydraulic Power Steering	Electric Power Steering
Heating	Electric Heating
Hydraulic brakes	Electric brakes
Belt driven cam shaft valves	Electric value actuation

Table 1. Mechanichal & Electromechanical Systems

4. IMPROVE ENGINE EFFICIENCY

The ICE is used to convert chemical energy of fuel into kinetic energy to move the vehicle. Improving engine efficiency is improving the amount of energy that is usefully converted into motion.

In slow moving traffic an engine remains at idle for long periods thus producing unwanted emissions and wasting fuel. If the engine on a hybrid is idling, the engine could be doing useful work to recharge the battery. A hybrid also enables the engine to be switched off when the battery is fully charged.

If the vehicle is moving at low speed, there may be sufficient power from the battery to drive the electric motor and move the vehicle. Thus removing the need to start the ICE.

As mentioned before hybrids allows the ICE to be downsized, this not only saves weight - the efficiency of the engine is also improved (e.g. a smaller engine which is working harder is more efficient than a larger engine). The electric motor is used to 'top up' the power from the engine. This topping up of ICE power has a limitation, it will only work when there is sufficient electrical energy in the battery.

If the battery on a hybrid vehicle becomes discharged, this 'top up' feature is no longer available. The vehicle is only powered by the ICE (which has been downsized) which results in lower levels of performance. Manufacturers sometimes quote vehicle power as a sum of maximum ICE power and electric motor power give a total power output. This extra power is also used in acceleration. This should be taken on the condition that this power is not always available. Think about the effect on vehicle response. For example what would happen if the battery be discharged during an overtaking manoeuvre? A dangerous situation could occur as well as driver dissatisfaction. The driver will be less confident with the vehicle due to power uncertainty. A method to remove/ minimize this characteristic is required. One option is to not downsize the engine. The electric motor would replace a fraction of the engine power, not supplement it (So not increasing total output power). However, this limits the benefits possible.

Table 1. Mechanichal & Electromechanical Systems

The summing of ICE and electric motor power should only be used if it is possible to maintain the battery charge so that there is always sufficient energy for an overtaking manoeuvre. However guaranteeing the availability of power and energy form a battery is not an easy task.

5.REDUCE ENERGY LOSSES

As the vehicle moves it will lose energy is through factors such as aerodynamic drag, rolling resistance and braking friction. Minimising these losses will reduce fuel consumption.

The brakes on a vehicle are where a large amount of energy is lost, as kinetic energy is converted into heat energy and dissipated. This is where the hybrid vehicle can gain the most benefit. Hybrids use regenerative braking to convert the kinetic energy into electrical energy that can be stored in the battery. The electric traction motor on a hybrid has dual function as it can act as a generator to charge the battery or provide electrical power.

The weight of the vehicle becomes less important if regenerative braking is fitted. In an ideal world all the energy used to accelerate the vehicle could be recovered by the regenerative braking. Thus the weight of the vehicle would not be that important. Also the extra weight of the hybrid components is not too important.

However it is not an ideal world, regenerative braking is not 100% efficient because:

- It is not possible to capture all the energy
- It is not possible to store all the energy

5.1. Capture all the energy

Regenerative braking generates the most power when the motor/generator operates at fixed high speeds. However this is not characteristic of typical braking. Even at high speeds the energy conversion is not 100% efficient, so it is not possible to capture all the kinetic energy.

5.2. Store all the energy

The rate at which the battery can absorb energy is limited. The battery must convert electrical energy into chemical energy. It is also not 100% efficient, the faster the energy transfer the greater the losses. Charge acceptance of the battery is dependant on the physical construction. Generally the capability to accept charge is related to the capacity. With a larger battery having higher charge acceptance than a smaller one. However the larger the capacity, the greater the weight.

Also the battery has limited capacity, at some time the battery will become full and no longer be able to store recovered energy.

6.SIDE EFFECT OF REGENERATIVE BRAKING

As mentioned before, if the battery is fully discharged, no power boost is available from the electric motor. Regenerative braking is affected in the opposite battery state, as no regenerative braking is available when battery is fully charged. This could again have an effect on vehicle handling, but regenerative braking should not be used to improve braking performance. The regenerative braking should replace a percentage of the full braking force. e.g. the stopping power will be 40% from regenerative braking and 60% from friction brakes under normal conditions, but if the battery is full charged 100% of the braking force will be from the friction brakes. As the vehicle slows the speed of the generator will reduce thus reducing it's braking effect, therefore the retarding effect of the friction brake must be increased. The ratio of braking from regenerative braking and friction braking must be dynamically adjusted during deceleration to avoid peculiar braking characteristics. This adds another complexity to regenerative braking.

However it is possible to use regenerative braking to improve braking performance if extra components were added to the vehicle. In this case, the power from the motor/generator could be simply dissipated as heat when the battery is fully charged, this is known as dynamic braking and is used in many applications such as trains and conveyor belts. Once again this will increase complexity and weight.

7. IMPLICATIONS ON THE ELECTRICAL SYSTEM

Hybrid Electric technology totally changes the electrical system on a vehicle.

The traditional alternator (electrical generator on a standard vehicle) is no longer used and is replaced with an integrated motor / generator to power the electrical systems and as an alternative to the alternator. Electromechanical systems are required on hybrid vehicles, as the ICE is not run continually.

As discussed previously, electromechanical systems such as electric steering and brakes will need to be fitted to hybrid vehicles, and therefore the electrical supply becomes safety critical. If the electrical power fails, systems such as the brakes and steering also fail, so the integrity of the electrical system must be maintained.

When the motor/generator is acting as motor, no power is supplied to the vehicle electrical system.. The motor/generator becomes a consumer of electrical power, and the battery must supply power for all electrical systems.

This has implications on the battery, if the vehicle power supply voltage was to drop very low (brown-out), then vehicle systems could fail. Therefore the battery is also a safety critical component.

The electronics content of cars has been ever increasing due to electromechanical systems and more comfort features, thus increasing the total electrical load. This inevitably tends to make the problem worse, and the performance required from the battery will become more demanding.

8. IMPLICATIONS ON THE BATTERY

The previous section has explained that the battery must be capable of powering all the electrical system of the vehicle. In this case a fully charged battery would be ideal to ensure electrical integrity. However to maximize regenerative braking opportunities the battery should be as 'flat' (discharged) as possible. Regenerative braking helps to reduce emissions through energy recovery and this opportunity should not be lost, therefore a flat battery helps to improve emissions.

These two extreme states causes a contradiction, therefore to ensure the battery is equally capable of both power supply and power storage, it should be at half capacity, which is commonly expressed as 50% (or 0.5) State of Charge (SOC).

Maintaining the battery at 50% SOC is running the battery in Partial State of Charge (PSOC) operation. However running batteries in PSOC tends to shorten the life of the battery. For example, in a lead acid battery, sulphation occurs in PSOC operation resulting in degradation.

The battery is running in a highly compromised state, since a fully charged battery is good for power assist and long battery life but the opportunity to recover energy is lost, the vehicle manufacturer must choose the compromise lower emissions or more power assist and longer battery life. This concept will be ned as '*Energy Balance*' in this paper.

The algorithm that controls energy balance is one of the most important considerations in the hybrid vehicle. It must decide on the compromises between emissions, safety, reliability, and battery life.

In order to maintain this energy balance, the State of Charge (SOC) of the battery must be determined accurately. Also the capacity of a battery tends to decrease with age, this being expressed as State of Health (SOH). So the SOC and SOH are important parameters for operation of a hybrid vehicle. The SOC is also needed to avoid overcharging the battery.

However there is currently no proven and reliable method to accurately obtain SOC and SOH for Hybrid use [1]. Although many methods have been proposed. [2][3][4][5]

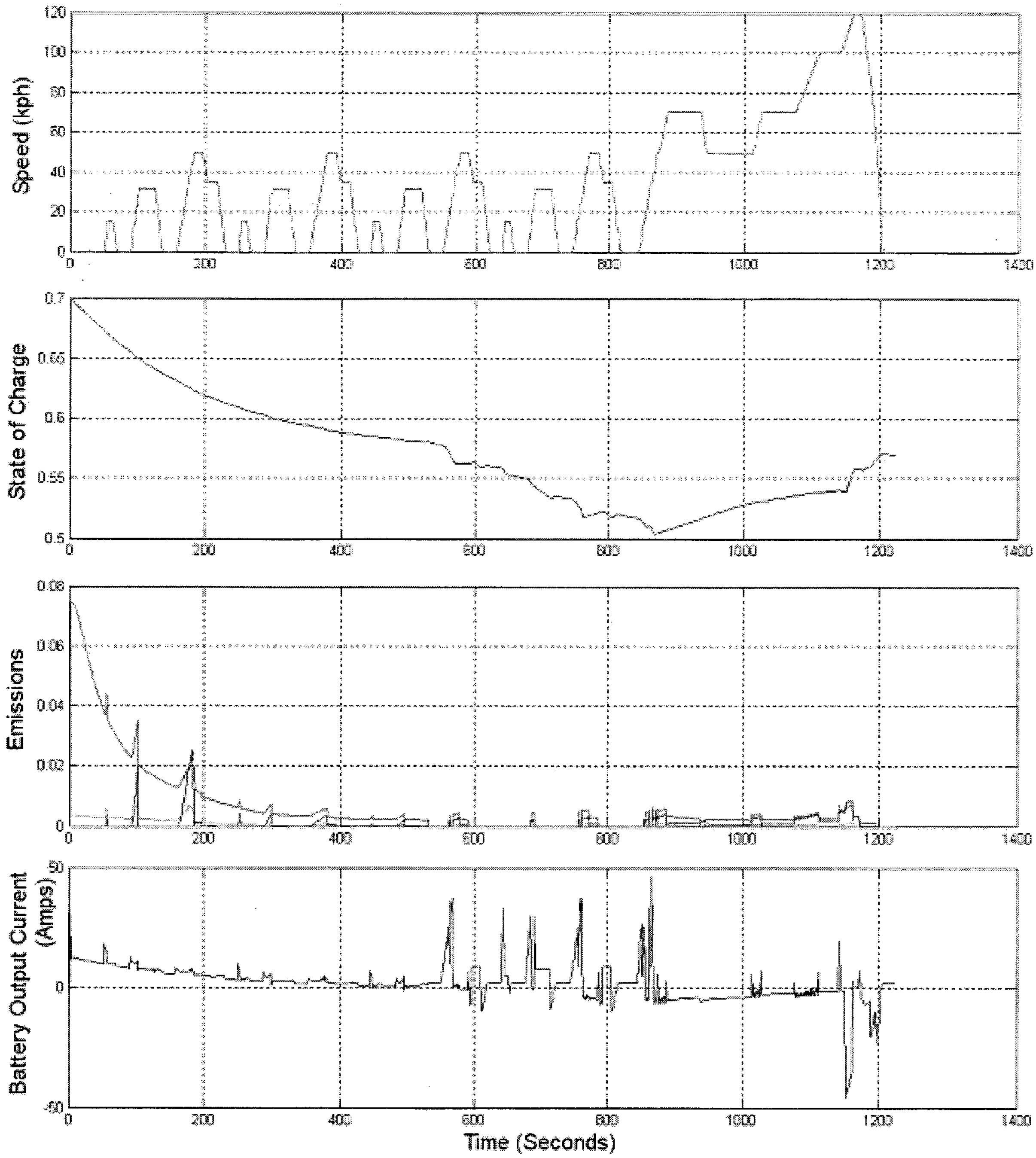

Figure 1. ADVISOR Simulation of a **Toyota Prius** *in the ECE15 + EUDC drive cycle*

A partial solution to this problem is to use two batteries that are isolated but able to transfer energy between themselves. The second battery is maintained at full charge for emergency situations. However this leads to more weight and complexity and with the high electrical content on a modern vehicle this battery is unlikely to be small in size.

9. HYBRID DRIVE CYCLE PERFORMANCE

The last section has shown how the operation of a hybrid vehicle is a compromise. So how well do hybrids perform?

Official emission and fuel economy tests are performed using the standard driving cycles, such as the ECE15 + EUDC drive cycle. A drive cycle is a speed / time profile used for vehicle testing with the vehicle being driven on a rolling road (dynamometer) according to the drive cycle profile. The emissions and fuel economy are measured during the test and quoted against the drive cycle used. The ECE15 + EUDC test is conducted in two sections urban (city) for the first half and extra urban (highway) for the second half. The complete test gives the 'combined' result. Figure 1 shows the profile of the ECE15 + EUDC driving cycle and simulated responses of a vehicle to that cycle. The top graph with the y axis is labelled Speed shows the drive cycle. The first 800 seconds represents the city part of the drive cycle (ECE15). This consists of stops and starts with low speeds. The remaining part of the graph from 800 to 1400 seconds, shows the high speed highway part of the drive cycle (EUDC – Extra Urban Drive Cycle). The other three graphs show the simulation of the *Toyota Prius* (First Generation).

The simulation results were generated using the ADVISOR 2002 Advanced Vehicle Simulator which runs under *MATLAB/Simulink*. ADVISOR allows vehicle parameters and subsystems to be changed and the performance on various drive cycles to be simulated. The simulations shown are based on an unmodified *Toyota Prius*.

Returning to figure I, the second graph with the y axis labelled 'State of Charge' shows the simulated SOC of the battery over the duration of the drive cycle. The third graph with the y axis labelled 'Emissions' shows the simulated emissions for the vehicle over the drive cycle. This paper will not go into a detail detailed description of each type of emissions, but the assumption can be however made that lower emissions are better for this plot. The fourth graph with the y axis labelled «Battery Output Current» shows the simulated output current of the vehicle battery. A negative current shows current flowing into the battery (charging). The State of Charge graph shows the energy balance for this drive cycle runs the battery between 70% and 50% SOC. Notice how the battery energy is gradually depleted during the city part of the drive cycle. This is where a standard vehicle is least efficient and produces the most emissions. The emissions are highest just after start up in a hybrid (as the hybrid still uses a ICE). However using the battery will avoid loading the ICE when it is cold and least efficient, and hence helps reduce emissions. To demonstrate this, the ADVISOR simulator was modified so that no electric motor assist was used and the generator was used to recharge the battery unit it was fully charged after 200 seconds.

The result was a 30% increase in fuel consumption and 24% increase in CO_2 emissions over the drive cycle. Therefore if the battery is heavily discharged at start up, the hybrid vehicle will perform in a similar way to the simulation above. This situation could occur through self discharge of the battery. A NiMH battery as used by the *Prius*, can self discharge from 100% to 70% SOC in 30 days if the battery is at 20°C. But if the ambient temperature is 45°C (which can be easily achieved in warmer climates) the SOC can discharge to 20% SOC in 30 days [3]. This self discharge is fairly linear, so if the battery is at 50% SOC and parked for two weeks the battery will become fully discharged. If this battery is required to start the ICE, it will not be able to do so at this point.

Returning to Figure 1, examination of the drive cycle between 600 to 800 seconds shows the vehicle reaches near zero emissions. The Battery Output Current graph shows high activity at this time. Up to 40 amps of current is being used to move the vehicle. Also regenerative braking is in effect as the negative trace shows current flowing into the battery. This is an example of how energy balance is used to reduce emissions.

However this reduction in emissions is not 'free', since the State of Charge graph shows SOC is dropping rapidly, and cannot be sustained for long. However the drive cycle switches to highway driving, thus allowing the battery to be recharged. Using the flat battery simulation discussed earlier it could be assumed that if the city driving is extended, the emissions would also increase. This raises the question, has the hybrid vehicle been designed for this drive cycle or real world driving where the city driving could last for longer than 800 second (13 minutes)? Also if a journey started and ended in a city, when would the battery be recharged? The drive cycle finishes with the vehicle slowing down from 120 kph. Here the full effect of regenerative braking can be seen from the Battery Output Current Graph (just before 1200 seconds), Almost 50 amps of current is driven into the battery. This illustrates what a hybrid does, it recovers energy that would normally be lost in braking, and limits losses when the engine is idling. This stored energy is reused when most power is required such as in acceleration and moving from rest, or when the vehicle is least efficient such as just after engine start up and stop start driving.

10. HYBRID VS STANDARD VEHICLES

The previous chapters have shown the compromises necessary to implement a hybrid vehicle. So how does the performance of hybrids compare to standard cars?

Table II shows a selection of cars available in the United Kingdom. These cars were chosen because of their low emissions, with the first two cars in the table, the *Toyota Prius* and *Honda Civic 1.4 IMA* being petrol hybrids. Diesel engines are more efficient than petrol engines and hence produce less CO_2 and have better fuel economy for equivalent output. However, they do produce more particulate emissions (soot) than petrol vehicles. Most of the cars in the table are diesel for low CO_2 emissions; the exceptions are the hybrids and the *Diahatsu Charade* which is a petrol powered micro car.

Vehicle emissions are not a high priory to most vehicle buyers and users, the most desirable cars are mostly the more powerful ones. However cost is in an important issue, and one feature of hybrid vehicles is that they have good fuel economy.

So how much better does a hybrid vehicle perform against a non hybrid vehicle: From the Table II, the fuel economy of the hybrid is worse than the standard cars in the extra urban cycle (highway diving) and better in the urban cycle (city driving). This is averaged out in the combined cycle where the fuel performance is more or less the same.

To summarise:

- Hybrids outperform diesels in slow city driving.
- Diesels outperform hybrids in fast highway driving.
- Fuel economy is more or less the same for combined driving (66.6% City, 33.3% Highway by time)

If the fuel economy is more or less the same, how can the extra cost of a hybrid be justified? This extra cost could be about £3000 (4200•) for an equivalent sized car (*Prius* Vs *Focus Diesel in Table II*). The difference will be higher if the *Prius* is compared with a petrol car. The *Honda Civic*

Vehicle	CO_2 (g/100km)	Urban (mpg / l/100km)	Extra Urban (mpg / l/100km)	Combined (mpg / l/100km)	Maximum Weight (kg)	Engine Power (bhp)	Acceleration (0 to 62mph or 100 kph) seconds	Price (British Pounds / Euros)
Toyota Prius	104	56.5 / 5.0	67.3 / 4.2	65.7 / 4.3	1300	76	11.5	£ 17545 (24563€)
Honda Civic 1.4 IMA	116	47 / 6.0	65.7 / 4.3	57.7 / 4.9	1264	89	12.8	£ 15100 (21140€)
Honda Civic 1.7 CTDi	134	44.8/ 6.3	64.2 / 4.4	56.5 / 5.0	1264	99	11.5	£ 14100 (19740€)
Citroen C2 1.4 HDi	108	55.4 / 5.1	78.5 / 3.6	68.9 / 4.1	1083	69	13.5	£ 9095 (12733€)
Citroen C3 1.4 HDi 16V	112	53.3 / 5.3	76.3 / 3.7	65.7 / 4.3	1058	92	11.7	£ 12745 (17843€)
Citroen C4 1.6 HDi	125	47.1 / 6.0	70.6 / 4	60.1 / 4.7	1379	108	11.2	£ 14895 (20853€)
Ford Focus 1.6 TDCi	127	45.6 / 6.2	70.6 / 4	58.9 / 4.8	1426	108	10.8	£ 14620 (20468€)
Ford Fiesta 1.4 TDCi	114	53.3 / 5.3	76.3 / 3.7	65.7 / 4.3	1167	67	16.2	£ 10395 (14553€)
Diahatsu Charade 1.0	114	47.1 / 6	68.9 / 4.1	58.9 / 4.8	740	58	14.1	£ 5695 (7973€)
Honda Accord 2.2 i-CTDi	143	42.2 / 6.7	61.4/ 4.6	52.3 / 5.4	1523	138	9.4	£ 18900 (26460€)

Table 2. Vehicles and Performance. Source: What Car Magazine (United Kingdom) [6] Technical Data on all cars on sale in the UK

Hybrid is cheaper than the *Prius*, but the performance is lower.

Hybrids have lower CO_2 emission than diesels for an equivalent sized car. The car with the lowest CO_2 emission is a hybrid car the *Toyota Prius* (104 g/ 100km). Even though the fuel economy is approximate the same the hybrids have an advantage in CO_2 emissions.

However this advantage comes at a cost, the *Honda Accord* has the most similar to price to the *Prius* in table II, but the *Accord* is larger, more powerful (twice the power) and faster, but it is only 20% less fuel efficient, and produces 30% more emissions. The quoted fuel and emission figures are not likely to be based on a fully loaded vehicle, considering how the hybrid system is a compromise between many factors (Energy Balance).

What would happen if the *Accord* and *Prius* were fully loaded with four people including 80kg of luggage? Has the battery the ability to balance the extra energy of a full load? Will the fuel economy and emissions still be better in the *Prius*?

If a buyer was choosing a car based mainly on the CO_2 emission. Would they buy a *Prius*? A *Citreon C2 1.4 HDi* has only a slightly higher CO_2 emission than the *Prius* by 4g/100km. It is smaller but it is also half the price of the *Prius*. To archive this CO_2 rating the *Prius* is fitted with extra electronics, motors, batteries etc. If the CO_2 used during manufacture is considered, the *Prius* is likely to produce more CO_2 during manufacture. Therefore is the *Prius* more environmentally friendly than the *Citroen C2*?

The above factors have lead to vehicle manufactures quoting the following about hybrid vehicles:

«*I see it [hybrid technology] as a niche application. It has it's uses in congested areas, but elsewhere you can achieve results that are good or better with diesel engines. Why would a farmer in Scotland or Wyoming, ever want to buy a hybrid ?* « Helmut Panke, BMW's Chief Executive.[7]

«*Hybrids area a small way of participating in the environmental debate but, economically speaking, you can't justify the cost. The incremental cost to the consumer is $3,000 to $3,500 [£1,660 to £1,940]. Diesels are a much better proposition.*» Jim Padilla, President of the Ford Motor Company.[7]

However, in America exhaust emission regulation is tough on particulate (soot) and oxides of nitrogen produced by diesel engines. This makes it difficult and expensive for vehicle manufacturers to produce diesel cars for the US market, thus an ideal market for Hybrid vehicles. However in Europe where the regulations are not as strict, diesels now form almost 50% of new car sales.

«*A full hybrid system adds 150kg to the weight of the vehicle. We need to reduce the cost and weight. We are also working on increasing the efficiency of our diesel engines – even with all the devices needed to meet the new American regulations the cost of those does not reach that of the hybrid*» Burkhard Goeschel, Head of R&D at BMW.

Current hybrids are not good enough; a possible direction for future research for hybrid technology could be:

- Reduce the cost of hybrids.
- Better energy storage systems for improved energy balance.
- Advanced systems for maintaining energy balance to counter act the additional weight disadvantage and offer improved performance.

A diesel hybrid could be a solution, but the extra cost of diesel technology and hybrid technology will be combined producing an expensive solution.

11. CONCLUSIONS

Fuel consumption and emissions can be reduced by:

1. Reducing weight
2. Improving engine efficiency
3. Reducing energy losses

Do hybrids really work? Hybrids can improve engine efficiency by balancing energy and engine downsizing. Hybrids can reduce energy losses through regenerative braking. However part of the benefit possible is lost through increased weight due to extra components required.

The electrical system in a hybrid is based on a battery which needs to be partially charged most of the time. Therefore battery monitoring and electrical system management is essential. The battery SOC and SOH are important parameters to monitor and maintain. Failure to do so will result in failure of the hybrid system when high or low SOC are achieved.

Petrol hybrids are more fuel efficient in city driving, but diesel engines are more efficient in urban driving. The biggest advantage of hybrid technology is its ability to reduce the emissions of a compact car to a level lower than a small city car, but with a large cost.

Due to the extra cost of the hybrid technology, it is difficult for hybrids to demonstrate extra '*value*' for the vehicle buyer.

Hybrids will need to be cheaper to become mainstream or offer advantages over diesels, this could be achieved by improving the energy balance of the hybrid for improved performance and better fuel economy.

However, there is not a technology better than hybrid technology. Diesel engines come close but there are the particulate and nitrogen oxide emission problems associated with diesel.

ACKNOWLEDGEMENTS

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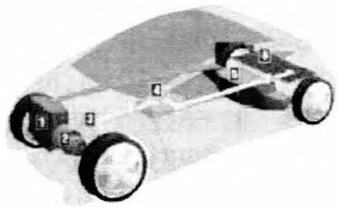
HYBRID VEHICLES: MECHANICAL ALTERNATIVES TO ELECTRICAL HYBRID VEHICLES



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ABSTRACT

The objective of this paper is to outline the major mechanical alternatives to electrical hybrid systems along with their advantages and disadvantages.

1.INTRODUCTION

This paper will be looking at the mechanical alternatives to electrical energy storage for hybrid vehicles. The main mechanical energy storage systems are hydraulic, pneumatic and flywheel. The paper will also look at their advantages and disadvantages compared to electrical systems.

2.DRIVING FACTORS FOR HIBRID VEHICLES

There are a number of driving factors for improving emissions and fuel economy in automotive applications. They include:

- CARB ZEV (zero emission vehicle) emissions regulations.
- The drive to reduce carbon dioxide emissions.
- The drive to improve fuel economy and reduce operational running costs.
- Western vulnerability to fluctuations in the price of oil.
- Emissions legislation outside CARB.

In the short term these can be met by improving engine technology but the improvements are small (10-15%) and the cost for more significant improvements is prohibitive. In the long term (15+ years) technologies such as fuel cell vehicles will provide for these needs. Currently the cost of this technology is expensive and unproven in the wider marketplace. Problems exist with a lack of infrastructure for refuelling. Hybrid vehicles provide the most viable medium term solution to meet the demands of the marketplace.

Hybrid vehicles have two power sources, usually an internal combustion engine and an electric motor. They can provide improvements in fuel economy and emissions for a reasonable cost. The improvements come from a number of factors including more efficient use of the engine and regenerative braking to reclaim some of the energy that would normally be lost to braking. Some systems allow the engine to be turned off during engine idles which improves the overall fuel economy [1]. As hybrid vehicles still use conventional engines as a power source the existing refuelling infrastructure is compatible.

3.HYDRAULIC SYSTEMS

Hydraulic systems are the second main focus of the car manufacturers (after electrical systems). Ford, Jaguar, Permo-Drive and PI technology are some of the companies working on hydraulic hybrid systems.

In a hydraulic system, energy is stored in a hydraulic accumulator using high pressure fluid. A hydraulic accumulator is a reservoir of hydraulic fluid which can store a variable volume of fluid at high pressure. Hydraulic motors and pumps replace the electrical motors and generators. Hydraulic technology is well established in other applications (such as mechanical diggers). The focus of current research is how to adapt and improve the technology for automotive applications.

The following components are added:
- Hydraulic accumulator
- Hydraulic pump/motor
- Hydraulic pump (series only)
- Hydraulic control servos

The following components are deleted:
- Starter motor
- Starter ring
- Large battery (replaced by smaller unit)
- Heavy duty electrical cables (replaced with lower duty cables)
- Gearbox (series only)

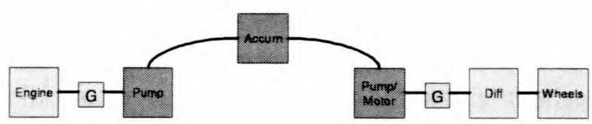

Fig. 1 Series hydraulic hybrid schematic

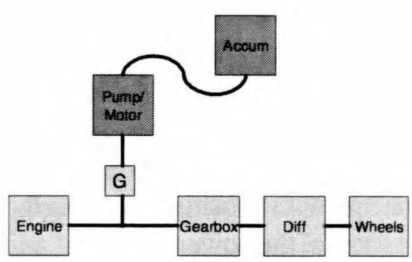

Fig. 2 Parallel hydraulic hybrid schematic

The efficiency of the system is a combination of the accumulator efficiency and the pump/motor efficiencies. Energy is lost from the accumulator as heat. To reduce this the accumulator needs to be insulated, often elastomeric foam is used. With a basic system a single motor is used. More advanced systems use multiple motors to improve the efficiency.

Hydraulic systems have the following advantages compared to electrical systems:
- Less expensive
- Accumulator life is better than battery life. The efficiency, power density and energy density are less affected by use.
- Better energy storage efficiency. Well insulated accumulators can have efficiencies above 95%.
- Better energy and power densities than electrical systems.

Hydraulic systems have the following disadvantages compared to electrical systems:
- There are some minor safety concerns with regard to ensuring a safe failure mode, for the hydraulic accumulator, during a crash.
- Does not qualify for CARB ZEV credits.

4. PNEUMATIC SYSTEMS

Research into pneumatic hybrid systems is relatively new and it is the technology that has been least developed by the main car manufacturers. One of the reasons for this is that most of the systems require a fully variable valvetrain. As the cost of these systems reduce with time/mass production the pneumatic systems will become more and more viable.

Pneumatic systems store energy in the form of compressed air. Two types of system can be used. The first operates in a similar way to hydraulic systems but instead of hydraulic pumps and motors, pneumatic compressors and pumps are used. There is little research into using these for hybrid systems due to their poor efficiency and bulk compared to hydraulic systems.

The second system uses a modified internal combustion engine as the pump/motor. An air storage tank is connected, through an additional valve, directly to the cylinder or through a switching air intake system. The majority of systems have fully variable electro-hydraulic valvetrains. The valves must be able to open/close with sufficient speed and be able to work with the high forces created by the pressurised system.

The air is stored in a large tank. The tank can be insulated or filled with elastomeric foam to reduce the energy lost as heat. Some systems flow exhaust gas around the air tank to control the pressure and temperature of the gas in the tank. If the air is too hot it can cause detonation when the engine is operating in modes using the compressed air during a combustion cycle. Figure 3 shows a schematic of a pneumatic system.

The following components are added:
- Air tank and piping.

- Electro-hydraulic valve system.

The following components are deleted:

- Starter motor.
- Starter ring.
- Cam system.
- Large battery (replaced by smaller unit).
- Heavy duty electrical cables (replaced with lower duty cables).

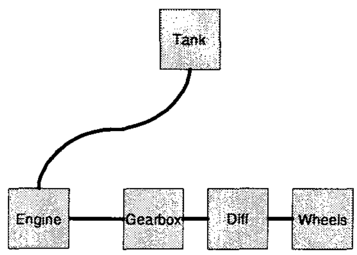

Fig.3 Pneumatic hybrid schematic

The engine can operate in a number of modes:

- Conventional running.
- Air pump mode/Compression braking.
- Air motor mode.
- Air power assist mode.
- Supercharged.
- Undercharged.

With electro-hydraulic valves the engine can operate all the modes as two or four stroke cycles.

The pneumatic system/electro-hydraulic valves also allow the following functions: mixed modes, cylinder deactivation, secondary air injection and internal EGR. Pneumatic systems benefit from the same advantages due to starter motor deletion as hydraulic systems.

4.1. Conventional Running

When running conventionally the engine runs exactly as it would in a normal vehicle. The introduction of a camless valvetrain increases the performance, fuel economy and emissions compared to a conventional engine with a cam driven system [1]. The fully variable valves allow the engine to operate in two or four stroke modes, deactivate cylinders and reduce the pumping losses.

4.2. Air Pump

When the vehicle is braking, the engine is operated in a compression braking mode. The engine produces a negative torque by compressing the air and storing it in the air tank. Air is drawn into the cylinder from the atmosphere, compressed and exhausted to the air tank. Depending on the torque required the engine can be run in both four and two stroke modes. No fuel is injected while operating in air pump mode.

4.3. Air Motor

When operating in air motor mode compressed air from the air tank is introduced into the cylinder provided the driving torque. The air is exhausted into the air intake or the exhaust depending on the specific design. No fuel is injected when operating in air motor mode. The air motor mode cannot provide as much power as air assist mode [3].

4.4. Air Power Assist

With the air power assist mode (four stroke) the engine runs with a positive pumping loop which provides some of the power. The air is added from the tank and exhausted (when combusted) into the exhaust system. If the system has a valve directly into the cylinder then a direct injection system is needed.

4.5. Supercharged

When short periods of high power are required during conventional operation the engine can be supercharged by adding high pressure air during the induction part of the cycle. This has the same benefits as conventional supercharging but without the need for additional components or power losses. It is limited to short periods of operation only due to the limited amount of compressed air stored. By adding the air later the pumping losses can be reduced [4].

4.6. Undercharged

When operating at part load during conventional operation the undercharged mode can be used. When operating in undercharged mode some of the air compressed prior to combustion is diverted into the air tank.

Pneumatic systems have the following advantages compared to electrical systems:

- The emissions and fuel economy are improved during conventional running due to the variable cam system. [1]
- The engine size can be reduced as the supercharged, air power assist and two stroke modes produce more power. This enables lighter, cheaper and more efficient engines to be used.
- No additional propulsion source needed [1]
- Pneumatic systems are the simplest and lightest of the hybrid systems [1, 5, 6].
- Pneumatic systems are cheaper than electrical systems. They are the cheapest of all the hybrid solutions and, if the vehicle has an existing variable valve system, they can actually be cheaper than the original vehicle (due to starter motor deletion).
- Better energy and power densities than electrical systems.

Pneumatic systems have the following disadvantages compared to electrical systems:

- If air is sent down the exhaust system, it will have a negative impact on the emissions due to catalyst cooling. In addition to this the catalyst will be oxygen rich, which will have a negative impact on NOx, but will improve hydrocarbon emissions when the engine returns to conventional running.
- There could be problems with robustness of switching valves in the high temperature/corrosive environment of the exhaust [1].
- There must be sufficient force for the valve to hold closed while the system is pressurised [5].
- Electro-hydraulic valve systems have higher energy consumption than a conventional cam system but the overall benefits of the system outweigh this.
- There are some safety concerns, regarding the venting of the compressed air, in the event of a crash.
- A large volume air tank is needed to store the energy.
- Pneumatic systems have poor energy density and control [5].
- The durability of the engine being used as a pump needs to be proved [6]
- Does not qualify for CARB ZEV credits.

5. FLYWHEEL SYSTEMS

Flywheel systems were a main area of research in the 1970s by companies such as Leyland trucks and buses. For a number of commercial and technological reasons flywheel systems were never fully introduced at this time. Developments in control methodology and materials technology mean that flywheel systems are once again viable hybrid options. The US department of defence and science applications international corporation are some of the companies currently working on flywheel hybrid systems.

In a flywheel system energy is stored in a rotating flywheel. The majority of current work in this area focuses on composite flywheels, as part of electrical devices. Flywheels can also be used in a purely mechanical system, using CVT (continuously variable transmission) or IVT (infinitely variable transmission) transmissions.

Figures 4 and 5 show typical flywheel hybrid schematics.

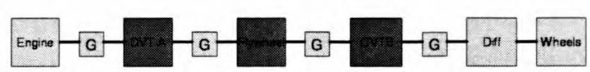

Fig.4 Series flywheel hybrid schematic

The following components are added:

- Flywheel.
- Bearing.
- Vacuum pump.
- Flywheel casing.
- CVT/IVT.

The following components are deleted:

- Gearbox (series only).

For maximum efficiency the flywheel needs to operate in a vacuum chamber. The overall efficiency of the system is limited by the CVT/IVT efficiencies.

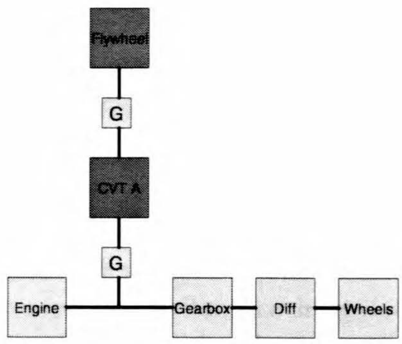

Fig.5 Parallel flywheel hybrid schematic

Pure flywheel systems have the following advantages compared to electrical systems:

- Less expensive
- Flywheel life is better than battery life. The efficiency, power density and energy density are less affected by use.
- Better energy storage efficiency. Efficiencies above 98% can be achieved.
- CVT/IVT have better efficiencies than electrical generators/motors.
- Better energy and power densities than electrical systems.

Pure flywheel systems have the following disadvantages compared to electrical systems:

- Energy dissipates between trips.
- Starter motor deletion is not possible.
- There are safety concerns with regard to ensuring a safe failure mode, for the flywheel, during a crash/failure.
- Does not qualify for CARB ZEV credits.

6.CONCLUSIONS

Hybrids are the medium term solution to meet the legislative and commercial needs in the marketplace. Mechanical systems are not as developed as electrical systems and do not qualify for CARB ZEV credits but they offer cost weight and efficiency benefits compared to electrical systems.

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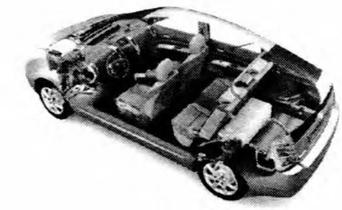
HYBRID ELECTRIC VEHICLE CONTROL: GENERAL CONCEPTS AND A REAL WORLD EXAMPLE



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ABSTRACT

The main objective of this paper is to explain the general concepts and analysis behind hybrid electric vehicle (HEV) control. Systems, components and concepts will be explained in order to illustrate the important position that this research currently plays in the environment of HEVs. Hybrid control strategies will be classified and current research considered in order to forecast future trends in this area. A real world example will also be provided, illustrating the key concepts and discussions of the publication.

Index Terms— Hybrid Control, Hybrid Control Strategies, CHOICE project.

1.INTRODUCTION

The emergence of *Hybrid Electric Vehicles* (HEVs) has opened new doors in the area of automotive research, and the control of HEVs is one area attracting a lot of interest. Due to the range of options possible in HEV control, there have been a variety of concepts developed, making it difficult to give a generic explanation which encloses them all [1].

However, this paper illustrates the general concepts currently involved in the optimisation of HEV control. The common parameters along with the techniques being implemented will be discussed in order to identify the common best practice. Also a description of a novel hybrid control project will be provided; with the objective to show possible parameters which could be taken into account in future HEV control strategies.

The CHOICE (City Hybrid-electric bus with Optimised efficiency using Information and guidance systems for passenger Convenience and vehicle Energy consumption) project has been undertaken in the group to which the authors belong. The aim of this project is to use collected data such as the speed and passenger information in order to optimise the fuel efficiency and reduce the exhaust emissions of the bus [2].

This paper is presented in two main sections. The first part will cover the control in HEV taking into account the elements and possible strategies involved. A real project illustrating the concepts of HEV control (CHOICE) will be explained in the second section.

2.CONTROL IN HEV

It is generally possible to observe whether the outcome of a system is actually what would have been predicted, based on a particular input or demand. If the outcome is different, then a method of control must be implemented in order to provide the necessary corrections and adjustments. The *control system* in a predominantly electrical device such as in an HEV operates in *real time* based upon real events during operation.

Apart from the common tasks that the HEV *control system* has to handle with respect to a normal control system such as safety issues, there are other methods and operations which are worth noting. The *HEV strategy* is the most interesting as it needs to determine which energy source/s need to be used when the car is driven, and the extent to which energy is recovered in braking. The area of

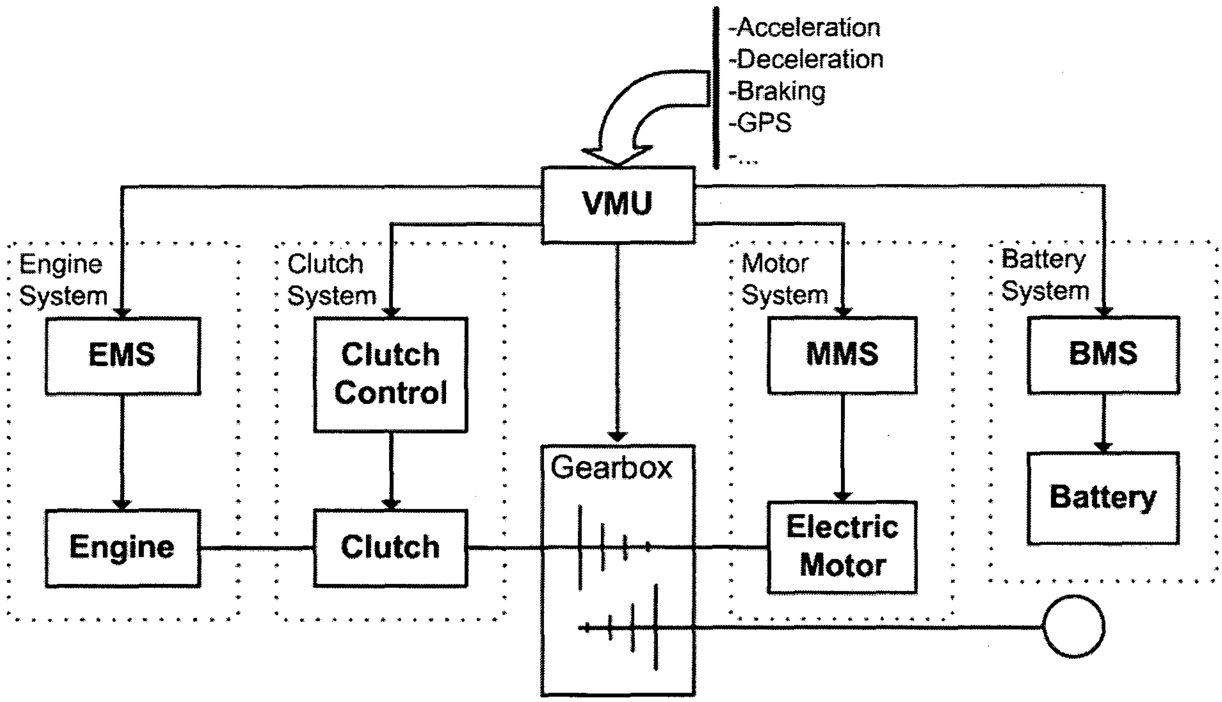

Figure 1: *General Hev Control Diagram*

HEV control within this paper will primarily be focused on the analysis of the current parallel HEV configurations. In order to cover this area it is important to introduce the following concepts:

2.1.Elements

There are several systems which are involved in the control system of a HEV. Figure 1 illustrates a general interconnecting scheme along with their functional connections. The *Vehicle Management Unit* (VMU) is considered to be the key part of the control system, as it provides high level management of all of the other system components. Each system is responsible for one element, meaning for example the engine, clutch, electric motor and battery are monitored for each system management configuration; explained further in the following subsections. The events or request responses are reported to the VMU which in turn makes an operation decision. The communications between the systems and the VMU are generally realised over a communications bus, typically a *Control Area Network* (CAN).

2.1.1.Vehicle Management Unit(VMU)

The *Vehicle Management Unit* (VMU) is considered to be the *brain* of the vehicle. The VMU collects and processes the necessary data from the other systems including the *Battery Management System* (BMS), *Motor Management System* (MMS) and *Engine Management System* (EMS) in order to decide the best response for each individual event. When the VMU makes a decision, it communicates with the necessary system/s which are responsible for the final execution. Therefore, the VMU implements the control within an HEV, thorugh the systems peripherals which provide data to the VMU and execute its orders.

Essentially, the VMU is responsible for the following tasks [3]:

- As shown in Figure 1, the VMU must detect the basic intentions of the driver. In other words, it must detect acceleration, deceleration, and braking demands in order to regulate them.
- The VMU controls the synchronisation of the system during the gear shifting process.
- In a parallel HEV, although not drawn in Figure 1, the VMU is responsible for the traction drives. This allows for the safe

operation of the drive components, such as the traction battery, by monitoring the system with the VMU. With this, modern-day dependency and reliability can also be achieved for alternative drive configurations.

- The VMU must implement the HEV strategy, as explained above. This strategy governs the choice between electric motor, internal combustion engine (ICE) and a combination of them both depending on the inputs and data requirements of the systems.

Concluding, the VMU, through the implemented embedded software, coordinates the correct working operation of all of the systems in the vehicle and integrates their operation for best effect.

a) BMS Function

A good definition for the *Battery Management System* (BMS) function is a subroutine or system to increase the battery's life, preventing it from facing serious dangers [4]. Also, the BMS function includes an estimation of the battery status. Therefore, the main objectives of the BMS function include:

- Protect the cells or the battery from damage.
- Prolong the life of the battery.
- Maintain the battery in a state in which it can fulfil the functional requirements of the application for which it was specified.
- Estimate the battery cell status in terms of both capacity and ageing.

In contrast, through a number of introduced concepts, it is possible to describe the battery status, the definitions of which are introduced here:

- ***State of Charge* (SOC):** The SOC is the *remaining capacity* of the battery and it represents the energy level remaining for useful work output. SOC is the ratio between the remaining capacity and the initial (rated) capacity of the battery, with this value usually being represented as a percentage.

- ***State of Health* (SOH):** SOH is the current condition of the battery. It can be determined as the remaining lifetime or the percentage degradation from the initial (rated) lifetime of the battery.

- ***State of Function* (SOF):** SOF is a measure of battery to perform vehicle functions, such as starting the engine. SOF is determined by both values for SOH and SOC, once determined the SOF shows what the battery is capable of delivering in vehicle terms. The SOF can provide the relationship between required current and time, whilst taking into account the whole health issues concerned with the battery. With these considerations the VMU can determine how long it can source predetermined current. Obviously, if the demand for current is high, the time will be low and vice versa. The SOF relationship is becoming widely used in the automotive industry due to its clear reporting capability [5].

Basically, the VMU is able to estimate the battery status (SOC, SOH and SOF) from a variety of parameters which are possible to sample. This status will be discussed further in order to take into

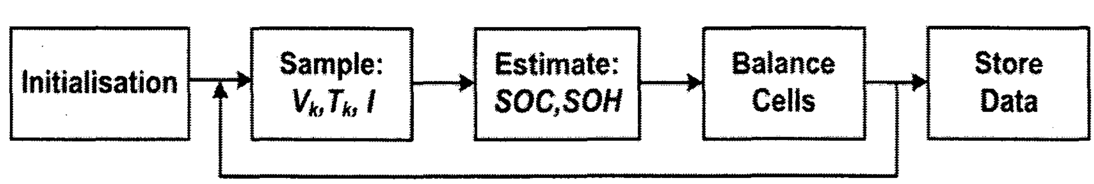

Figure 2: BMS Functional Diagram

account required energy needs or charging of the batteries, depending on the situation.

Figure 2 shows a block diagram of the functional working system of the BMS. Each time the subroutine is restarted, the BMS is initialised to its original settings. The previous load of the last parameter is captured and observed; in order to ensure the system operates as two subtasks. The following sample is an important operation of the BMS which is explained in-depth.

(1) Sample

Over the connection between the BMS and VMU through the CAN bus, the VMU receives a sample of the open circuit voltage and/or the current. Current within a battery system is a common parameter, whereas the voltage needs to be captured for each cell in order to estimate the SOC and SOH. The other parameter of concern is the temperature, which also needs to be sampled in order to protect the battery. The operation of the CAN interface is controlled by the BMS, and is covered in the following section.

(2) Estimated SOC and SOH

The key process in estimating the SOC and SOH is through sampling the previous voltage and current values; this can be achieved through certain techniques. Such options include the working of neural networks or fuzzy logic, both of which are currently attracting a lot of research in order to gain the appropriate knowledge to implement such approaches. Both of these approaches offer an array of flexibilities including the ability to predict future outcomes easily; however their current weaknesses lie within the area of testing [6]. These options are conventional static techniques and they frequently use data recorded within a laboratory environment; applying different cycle tests to a variety of cells to simulate real life conditions. As a result, these experiments produce characteristics such as the relationship between the open circuit voltage and the current to give the SOC and SOH [7].

In order to determine SOC the current must first be integrated in order to measure change in current from battery operation. The fundamental equation in order to use the current integrator technique to estimate the SOC is:

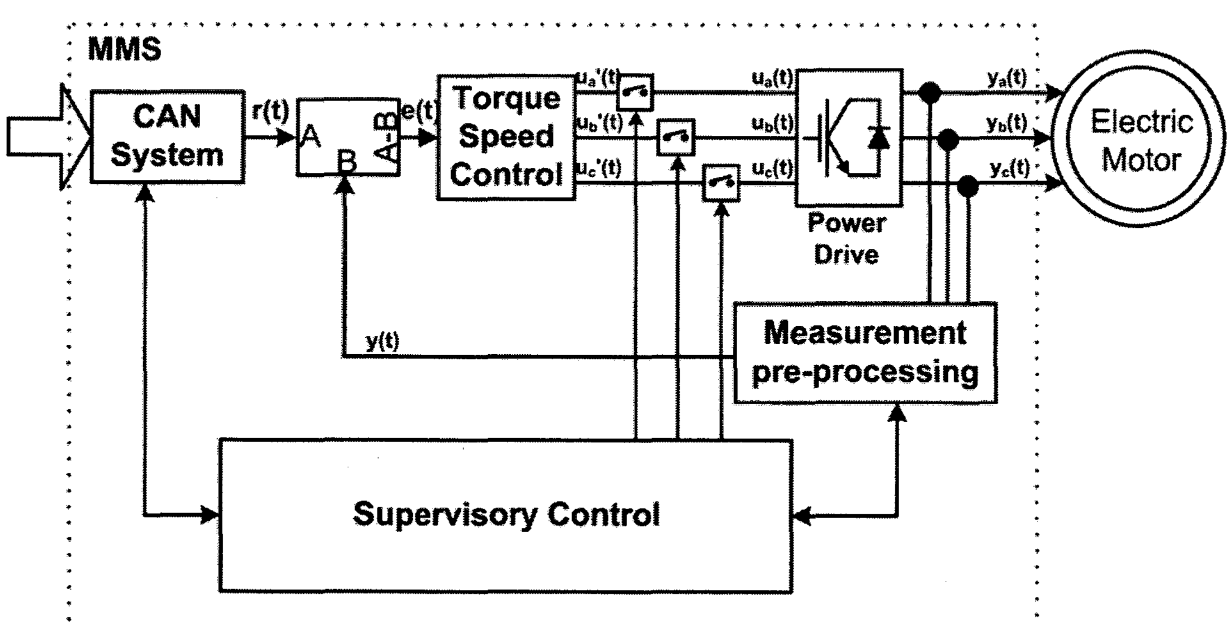

Figure 3: MMS functional diagram

$$SOC = \frac{Current \quad Cell \quad Capacity}{Total \quad Cell \quad Capacity} = $$

$$= \frac{\int_{s}^{f} Idt}{Total \quad Cell \quad Capacity}$$

Here, t_s is the sample time and I is the current measured from start to finish. The variation in the *Total Cell Capacity* over a measured period of time represents the SOH. The SOH parameter is frequently monitored in order to estimate its changing value with respect to the gradually depleting charge capacity, experienced by the cell. This evaluation also requires the sampled temperature as well. In contrast, the voltage and current are two parameters which can estimate the SOC by themselves, or as a combination.

(3) Balancing the Cells

In many instructions of electrical devices such as CD players or digital cameras, it is advised not to mix new cells (100% SOC) with old ones (e.g. 20% SOC) as this would shorten the useful lifetime of the new cells. For HEV applications this is no exception, and this problem must be controlled by within the BMS system.

The sampled voltage for each cell is determined in order to obtain an estimation of the SOC for each cell. The cells can then be matched in terms of their charge. Although the benefits of this practice are undoubtedly noticeable, there are still issues concerning the cost involved in implementing this into the BMS.

(4) Data Storage

The stored data within the BMS can be used in order to improve the general behaviour of the BMS function; storing the data and creating an historical log for future predictions. For example, the *Kalman* filter application in the SOC, SOH and SOF estimation is an important research area in the BMS environment which requires the collection of such data [8].

b) MMS and EMS Functions

The MMS and EMS functions control the power and energy requirements of the electric motor and the internal combustion engine (ICE). This operation is further controlled by the VMU based on the inputs such as acceleration or braking along with the data from other systems such as the SOC, SOH and SOF of the batteries. Generally, the VMU aims to operate the ICE at its peak efficiency through the EMS function, maximising the advantages for the HEV.

The EMS and MMS functions also report any special event/s to the VMU such as abnormal operation in order to maintain proper working order. As noted previously the communication is performed between the system (MMS or EMS) and the VMU over a communication bus standard such as CAN.

2.1.2.Battery Management System(BMS)

The *Battery Management System* (BMS) exists as a VMU function within the framework of the HEV control system. The BMS includes the necessary electronic devices to monitor the parameters, as previously explained for the BMS functions in the VMU. Depending on the kind of estimation that the BMS is going to execute, the sampling of the voltage and/or current will be necessary. The temperature is also required to be sampled, in order to estimate the SOH.

There are several devices which can sample both the voltage and currents, however only small selections of them are able to work with the high current and voltage levels, due to the difficulty of measuring the dynamic range of current. A *Hall Effect* sensor is generally used to capture the current, whilst an electronic based optocoupler design is an excellent choice to estimate the open circuit voltage for each cell. The advantages of an optocoupler are the high gain and current transfer that the device offers.

There are experts who consider that the BMS should provide conditioning as well. This conditioning process consists of repeatedly charging and deep discharging a battery for the purpose of preventing voltage depression or *memory effect*,

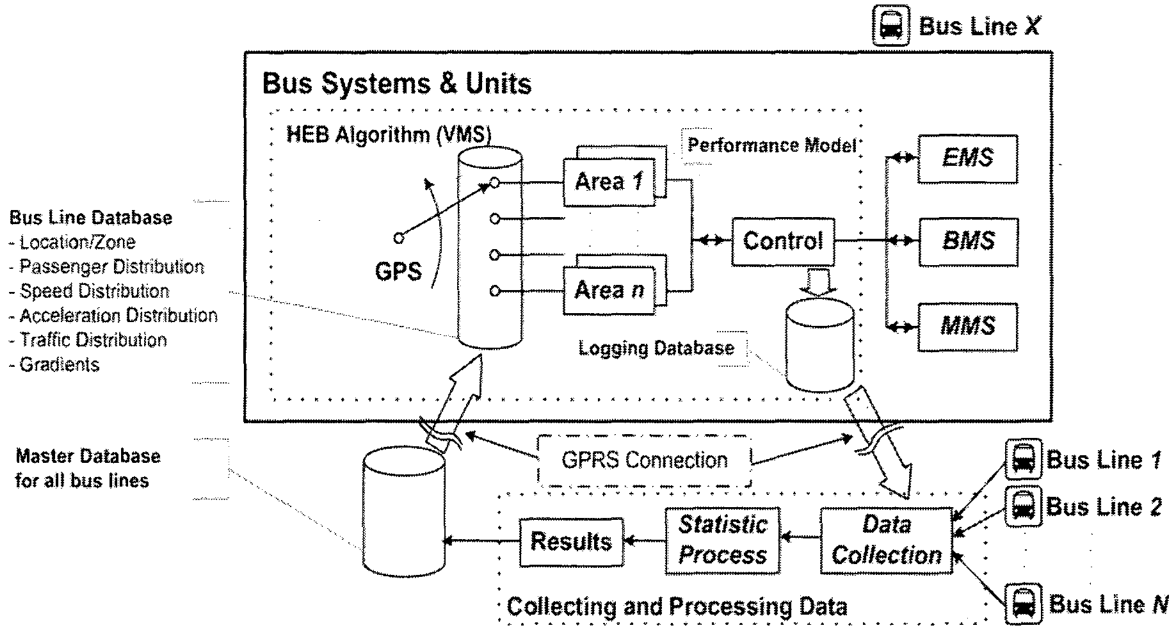

Figure 4: CHOICE Implementation Details

otherwise restoring lost capacity and maintaining a healthy cell balance.

2.1.3.Engine Management System(EMS)

The *Engine Management System* (EMS) (if fitted) is responsible for the fuel injection, ignition and the turbo issues concerned with a conventional engine. The control of the ICE is its main task and obviously it has contact with the VMU in order to report the necessary events. In contrast, the VMU must communicate back driver demands such as acceleration and braking.

In an HEV the VMU may divide the driver's required acceleration demand between the electric motor and ICE, and this is transparent to the EMS.

2.1.4.Motor Management System(MMS)

The objective of the *Motor Management System* (MMS) is to facilitate the electric motor control required by the VMU, and to supervise the correct performance of it [9]. The type of control is always determined by the electric motor type which is usually permanent magnet and synchronous alternating current (AC) in HEVs, to enable smoother operations between levels of the control system.

Figure 3 shows a block diagram with the main functional tasks of the MMS, which are described further below. The *CAN system* is responsible for interpreting between the MMS and VMU and vice versa. Basically, the power demands for the electric motor provided by the VMU is translated to the *r(t)* signal, it also has direct contact with the *Supervisory Control* block to warn the VMU of any abnormal events.

The *Torque Speed Control* is the real control part of the loop, with the objective of supplying the three controls signals necessary for the electric motor, once amplified in both current and voltage for the *Power Drive*. The *Measurement pre-processing* is responsible for two tasks. The first is to retranslate the three control signals ($y_a(t), y_b(t)$ *and* $y_c(t)$) into $y(t)$, in order to differentiate the signals which will improve the accuracy within the feedback process. Secondly, to keep in contact with the *Supervisory Control* for safety issues; operating as a switch between the blocks if necessary.

In other words the MMS is undertaking the control of the electric motor when it is operating. The way in which this is achieved is beyond the scope of this publication; however this can be referred to in [10].

2.2. HEV Strategy

The choice of energy source/s for a particular HEV is governed by the HEV strategy of the vehicle. By employing an appropriate strategy, the HEV will gain the most benefits whilst avoiding any decreased performance effects. One area which is monitored and controlled by the HEV strategy is the state of the batteries. It is crucial to keep the batteries in a healthy state in order to protect the complete system from premature deterioration and therefore maintain the efficient working life of the batteries. Therefore, a well designed algorithm could optimise the process, and help to increase the benefits of the HEV application.

The process inputs are the stimulus provided by the driver. For example, if the driver is accelerating strongly, the VMU should use all energy sources. In contrast, if the vehicle is braking, the VMU should use this energy to recharge the batteries. In both cases, a good estimation of the cells status is a key point to decide the extent to charge or discharge the batteries and hence increase their life.

The three key areas under which this research lies fall under the following categories [11]:

- **The use of intelligent control techniques:** *Fuzzy logic* and *Neural Networks* are just two examples within this line of research [12], [13].

- **The use of static optimisation methods:** Basically, the electric energy in an HEV is handled like a fuel in terms of energy cost [14], [15]. This method optimises the proper energy and/or power split between the two energy sources used. As the optimisation of this process requires relatively little computational effort, the emissions can also be reduced by a greater extent as well [16].

- **The use of dynamic optimisation methods:** Generally speaking, these methods use the dynamic nature of the system, in order to realise the optimisation of such with respect to time. In general terms, this technique is far more accurate than the previous static one [17], [18].

2.2.1. New Trends

New trends have begun to see the use of electronic devices such as GPS (Global Positioning System) in order to try and improve the HEV strategy. In fact, there are previous projects developed within the authors' group which support this idea. For example, the *CHOICE* project has the objective to develop a *hybrid electric bus* (HEB), as it may well provide a useful tool for optimising HEV transportation systems and other vehicle systems in general [2]. Factors such as the weather, the speed distribution, the passenger distribution and most obviously the global positioning are being taken into account in the HEV strategy of these buses.

3. A REAL WORLD EXAMPLE: CHOICE PROJECT

The *CHOICE* project is a collaborative project between a number of industrial and academic partners. The overall aim of which is to specify, design, build, test (in a full service environment) and evaluate a diesel series hybrid electric bus (HEB).

The vehicle's energy usage (and hence efficiency and emissions) is to be optimised through advanced engine and battery control techniques, which in turn make use of a range of input information. Additionally, the HEB will make use of current and future telematics technologies to assist in the optimisation of the efficiency. The key targets for the project are:

- Enhanced traffic system information, including clear performance zone switching & route guidance.

- Reduced emissions (exhaust) to Euro 4 (or lower) legislative limits (2006).

- Reduction of fuel consumption and CO_2 emissions by a minimum of 30%.

Therefore, this project should provide a good case study upon which to predict future trends in HEV technology.

3.1.Implementation Details

The most desirable input for the HEV strategy control is an accurate power prediction. If this parameter is forecasted correctly, the HEV control could manage the available energy sources effectively for optimum effect.

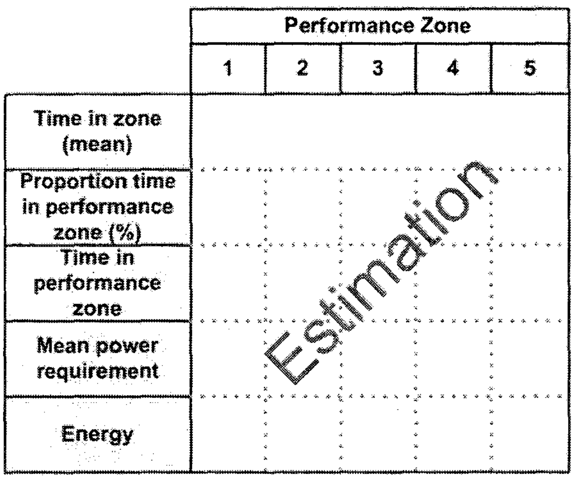

Fig.ure 5: Energy Profile for Traversal of a Geographic Zone

The CHOICE project estimates this power by collecting the necessary data and statistically processing it. This is possible due to the high correlation with the buses behaviour over time for the same route, as there are a number of aspects which will be roughly the same for each individual journey, such as the road surface and average speeds for example.

Figure 4 illustrates a general block diagram of the HEV control strategy developed in these buses. This representation can easily be divided in two sections; 1) *collecting and processing data* and 2) *HEB Algorithm (VMU)*.

3.1.1.Collecting and Processing Data

This first strategic step is developed outside of the bus, in two stages as the *collection of data* and the *statistical processing* of data.

a) Data Collection

The first evaluation to take into account is the determination of the necessary data to get accurate power estimations for the journey. These estimations can be divided into two key classes:

- **Static journey data:** This is data that does not change from journey to journey, such as the roads used, location stops and the gradients of roads.

- **Dynamic journey data:** This is data that relates to the particular journey, and which will not be constant from journey to journey. These can be subdivided in to two subclasses:

  _ *Progression of the journey descriptors*: such as the positioning, speed and acceleration of the bus.

  _ *Events of the journey*: defining the main factors which affect a journey such as weather, passenger loads and levels of traffic.

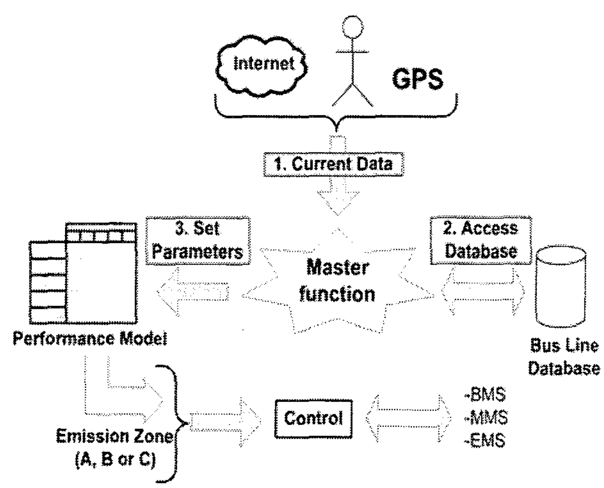

Figure 6: HEB Algorithm: Implementation details

For the first class (static data) the required information was collected using a route survey and maps of the area. This allowed the positions of major road junctions, bus stops, geographic features and speed limits to name but a few to be recorded. This information was then used for route classification purposes.

For the second class (dynamic data), collection was achieved through the use of a portable system (PDA), rather than an onboard or hard-wired system. This provided a greater degree of flexibility as the system could be used on any bus service without the need for costly or time consuming installations of the data collection equipment. Furthermore a fully automated system was not possible as a number of parameters were logged that are not readily available in an automated way, for example the number of passengers getting on and off at a particular stops, the weather and road traffic accidents.

These selections of data are collected for each bus route as there would be slight variances in results for individual routes. However, a number of the static data parameters are the same across the board, which makes the process of control easier to come to optimise (Figure 4).

b) Statistical Processing

When the data had been collected, the statistical analysis was calculated with the aim to estimate both the power and energy required for each situation. Due to the complexity of this process, the *performance zone concept* was introduced. This concept is captured and displayed in table (Figure 5).

In each column, the performance zones are separated to represent the varying bus speeds and the split in power requirements. The definition for each column is as follows;

1. 0 – 5 km/h, Performance Zone 1 (Creep zone): To represent slow moving traffic in a queue for a road junction or regular stop/starts, resulting in low average speeds.

2. 5 – 10 km/h, Performance Zone 2 (Crawl zone): To represent slow moving traffic at a junction as above, but with a steadier slow speed.

3. 10 – 20 km/h, Performance Zone 3 (Low speed zone): Typical inner city driving speeds.

4. 20 – 40 km/h, Performance Zone 4 (Medium speed zone): Typical urban speeds.

5. 40 – 80 km/h, Performance Zone 5 (High speed zone): Typical extra urban speeds.

The rows then go onto show the most important estimated parameters for each journey, (Figure 5). These parameters are processed statistically in order to work out the necessary averages, variances and percentiles; expecting that the correlation between journeys is high. Also, the grid is divided into different areas to classify the order of accuracy required for the differing power requirements between say the city and the motorway environment.

Therefore, the ideal performance model parameters are defined for all for all possible bus routes of the fleet. This obtained information is then stored in a master database. The performance model table for each bus route can then be loaded into the corresponding bus for any given journey.

3.1.2. The HEB Algorithm (VMU)

The HEB control is executed inside the bus VMU as previously discussed. Basically, this software manages the correct operation of a hybrid system; thus providing the best solution for each given situation. In other words, it optimises the fuel consumption and reduces emissions.

In the CHOICE project for example, the control system stored extra data which enabled the choice of the best strategy. This extra data has been described in the previous section and is stored in an internal database which distinguishes between the different bus routes (Figure 4).

Functionally, a master function loads these performance model table parameters whilst taking into account the different inputs, as shown in Figure 6. For example, weather (sun, rain….or fog), passenger distribution (0%, 25%, 50%, 75% or 100%), week day (Monday, Tuesday…or Sunday), time (1h, 2h or 24h) so on and so forth. The working area is fixed by the GPS, and set in a function which searches for the correct performance model table in the bus route database for these introduced parameters.

Depending on the nature of these functional inputs, these parameters can be introduced by internet (e.g. weather, unusual events...), GPS (e.g. current position) or manually (e.g. passengers loads) (Figure 6). Secondly, this function searches the database for the key parameters from the best performance model tables to provide information to the control system.

With the important objective of reducing the emissions especially within the city centre, the bus route has been divided into three types of operating regime; A, B & C. A represents a mandatory zero emission zone, B is ideally zero emission and C has no specific zero emission requirement. This parameter is provided to the control system as well in order to achieve the aim.

The control system based on the performance model tables (power and energy estimations) manages the emissions zones, battery output, electric motor and ICE management in order to establish the best possible solution for any given part of the journey. These control methods are also communicated back to the involved systems. Also, the control system logs a database in this process in order to generate a feedback approach to approve the accuracy of the process at each interaction (Figure 5).

3.1.3.GPRS Connection

To facilitate the connection between the master and the bus route database, the GPRS solution has been implemented for the CHOICE project. The logged database provided by the control system is recollected with this method as well. The advantages of GPRS are that you don't have to waste time on the move by constantly having to dial, whilst still being able to view moving images.

4.CONCLUSION

Undoubtedly, the control methods being introduced for HEV applications are offering advantages to electrical developments currently being implemented by other vehicles. For example, the global positioning and the maps of the software format found in the GPS car systems may be used in order to improve HEV strategies. For example, speed limits, crossroads and roundabouts are some usual parameters which can be obtained from GPS, and may be utilised in future energy and power requirement estimations. The method in which to make these predictions correctly is the key point in being able to improve current HEV systems.

The CHOICE project has been presented as an example of the extra data utilisation required in order to improve current HEV strategies. The research in *CHOICE* has been focused around hybrid electric buses (where the correlations between journeys are higher than those for cars); some of the statistical data and developments may however be useful in future HEV control systems analysis.

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AUTHORS

Diego Sánchez-Repila was born in Salamanca (Spain), in 1980. He obtained his Masters degree in Telecommunications Engineering from the University of Alcalá (Spain) in 2004. From 2002 to 2004, he was collaborating as Software Developer in a project supported by the Ministerio de Ciencia y Tecnologia.

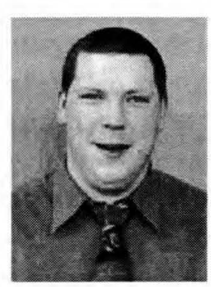
At the present time he is working as Research Consultant in the TIG group (Technology & Information Group), part of the WMG (Warwick Manufacturing Group) of the University of Warwick (United Kingdom). He has been an author of 5 articles in conferences, 3 of them international and 1 national article in the Spanish magazine Buran.

His tasks in WMG are focused in two different projects. On the first, he is working on the ISOLAB project, which has the main aim to develop a battery to meet the electrical power demands of future vehicles, which are able to support alternative installation and packaging strategies. On the other project, he is collaborating on the ECHOES project, which has the goal to use customer evaluation to help set engineering targets for the sounds of new vehicles.

John Edgar William Poxon was born in Chard (England, U.K.), in 1982. He obtained his Bachelors degree in Electronic Engineering from the University of Exeter (U.K.) in 2003. His final year project was to create web-based applications in the area of Communication Systems. This allowed students to work with interactive applets on communication theories online without the need for Matlab®.

His research area is focused within the field of hybrid electric vehicles on the Engineering Doctorate (EngD). His particular interests lie in the analysis of HEV modelling software, identifying possible areas to improve in the design process, and exploring the potential capabilities of high voltage HEVs.

He is a member of the Technology & Information Group (TIG). This is a research team based at the University Of Warwick in the Warwick Manufacturing Group's (WMG) International Manufacturing Centre (IMC). For the last 16 years they have been working closely with the automotive industry on a number of technology issues.



Stephen Baker was born in Manchester (UK) in 1975. He obtained his Bachelors degree in Physics from the University of Birmingham in 1996 which concluded in a final year project investigating the stability of sonoluminescence. This was followed by a Masters Degree in Manufacturing Systems Engineering in 1997 from the same institution. Since 1997 he has been a member of the TIG team (Technology and Information Group) based at the University of Warwick's Warwick Manufacturing Group.

His research interests have principally focused on a number of automotive based problems ranging from the Electromagnetic Compatibility (EMC) issues relating to composite and lightweight vehicles (an EPSRC funded Project), through to journey modelling for hybrid-electric buses (CHOICE Project).

More recently his research has centred on Sound Quality Engineering within the automotive sector. This includes the capture of customer opinion, and how this can be included early in the product design process. During this research he has assisted in the development of the groups product perception laboratories which includes a controlled listening environment and Noise and Vibration Simulator (NoViSim).

INTERVIEW: ADRIAN VINSOME

«Car manufacturers need to differentiate their products and HEVs are one mechanism to do this»

Adrian Vinsome started his professional career in Jaguar Cars Ltd in 1983, working as an Electronic Engineer in the Instrumentation Department. In 1988 he joined the University of Warwick as a Research Fellow, working in the Advanced Technology Centre's Electronics Group on engine management, journey prediction and hybrid vehicle development in collaboration with Rover Group.

In 1997 he joined the University of Durham to help establish and then lead a significant commercial consultancy operation, which expanded over a 5 year period until it employed 20 full-time staff. In 2002 he became involved in battery research for traction applications, and he is currently engaged as Project Manager for Hybrid Vehicle Research and Development in the Premium Automotive Research and Development Programme at the University of Warwick. He is a Chartered European Engineer with 20 years of experience in applied automotive research and development.

Buran: If you were to modify current HEV technologies, which component / system would you prioritise in adapting / changing first?

Adrian Vinsome: Commercially available HEVs represent the state-of-the-art in all of the associated technologies, so it is difficult to say which area needs changing first. However, the limiting technology at the moment still seems to be the electrical energy storage system, particularly the batteries. Research is needed to improve the cycle life, especially when the batteries are being exercised over a wide range of state of charge. In terms of development, I think significant improvements could be achieved with better battery management and control.

Buran: Do you think that current HEV models are too expensive for prospective customers? Do you think that the price is too high regarding the technology that they possess?

AV: There are two different questions there! HEVs are probably too expensive for the majority of customers at the moment, but these vehicles represent a great deal of R&D and embedded technology and I would argue that they are not too expensive for the technology that they possess. Also, the technology is still *relatively new, and volumes are low, so I think that we can expect to see prices fall before they level out.*

A lot of the on-cost in commercial hybrids is due to the batteries, typically Nickel Metal Hydride, and it is reported that both the battery manufacturers and automotive manufacturers are incurring a loss on these vehicles, but are accepting this because they see longer term gains as sales volumes increase. However, these battery chemistries will not fall in cost to rival lead-acid, and could even start to rise if demand outstrips supply. If the durability of lead-acid could be improved, the cost benefits of the technology would help to push down HEV prices and widen their acceptance, so this is one area of research that certainly warrants further investigation.

Buran: How effective is regenerative braking? Are there any specific areas which could be improved within this process?

AV: The big selling point of hybrids is that they are more efficient that a conventional powertrain, and this is largely because they can recover energy that would otherwise be lost as heat when braking. The braking power that a vehicle can achieve is several times higher than the power available for acceleration, and normal driving shows relatively high, but also short duration, braking power spikes.

The efficiency with which this energy is recovered is limited by the battery's charge acceptance, which is also a function of its state of charge. It may be possible to improve the energy recovery into the electrical system with a supercapacitor, either with or without a battery, but this will require careful management to gain the maximum benefit without damaging the components, and also adds further complexity. There is a lot of research needed to derive the best control strategy for a hybrid powertrain, and recovering the maximum amount of energy for reuse is a key consideration.

«In terms of development, I think significant improvements could be achieved with better battery management and control»

Buran: With Rover going bankrupt recently, and Fiat owing a significant amount of money, do you think that in order to maintain a creditable market status it is important to put a considerable amount of resource into more alternative vehicle types; for example HEVs?

AV: The automotive industry is extremely cost sensitive, and competition is very strong. Manufacturers need to differentiate their products and HEVs are one mechanism to do this. However, it is difficult to produce a sensible business case for hybrids because the benefits are very dependent upon the driving cycle and style, and also on the cost of fuel, since the savings have to be weighed against the additional cost. I think that governments in particular need to take a close look at incentives and actions that will promote introduction and market penetration. Once the manufacturers are confident that a stable opportunity exists, I'm sure they will invest in the technology.

«The other option, of course, is to investigate diesel hybrids to establish whether the benefits justify the additional cost and weight»

Buran: To your knowledge are there many car manufacturers investing in hybrid technologies? If so, which ones?

AV: Toyota is clearly leading the way with the Prius and Lexus RX 400h. However, Honda, Ford, GM and PSA have all released models with some level of hybridisation, and almost every manufacturer has demonstrated the technology at some point in the last 10 years. I would be surprised if any manufacturer wasn't *seriously considering the technology at the moment. It isn't only car manufacturers that are interested. In many cases, the commercial vehicle and bus manufacturers are ahead of the field in hybrid technology.*

Buran: Why do current HEVs have only permanent magnetic electric motors (synchronous alternating current), rather than any asynchronous types? What would you consider to be the significant advantages / disadvantages of each type?

AV: Asynchronous machines are still cheaper, will operate at higher temperatures, and have simpler control requirements that are still better understood by industry. Some buses use asynchronous machines, and I think the GM Silverado Hybrid does as well, so I wouldn't agree that current HEVs only have PM machines.

However, the main advantage of permanent magnet motors is that they offer high efficiency and high power density – packing a lot of power into a smaller electrical machine. They are more expensive than other electric machine types, but the cost is falling, so they are becoming more competitive on price. Packaging components is always an issue on modern vehicles, so the smaller size of the permanent magnet motors is likely to favour their use for new applications.

One significant disadvantage is that the magnetic materials cannot withstand high temperatures, and additional cooling will usually be required, especially for under-bonnet applications.

Buran: Biodiesel / Diesel vs. HEV, any comments on this matter? Do you take this matter into account when considering your research objectives; based on competitor's movements for example?

AV: Clearly, all research needs to be aware of what is happening in the market place, so it is important to track industry and market trends. Biodiesel offers a better carbon balance than fossil fuels, and I believe we will see more and more being introduced as a blend with conventional diesel. Diesels in general offer better efficiency than gasoline, and they account for about 45% of the new sales in Europe at present. However, gasoline is better than diesel for noxious emissions, with lower NO_x and particulates, and improvements in combustion technology are narrowing the gap. Automotive consultants Ricardo claim it is now possible to achieve diesel efficiency with a high compression (HCCI) gasoline engine. This is one development we'll be watching closely, since an HCCI/HEV drivetrain will offer benefits all around. The other option, of course, is to investigate diesel hybrids to establish whether the benefits justify the additional cost and weight.

«In gasoline based markets, such as the US, diesels are not popular because the public perception of them is very poor, and they are still associated with noisy, dirty trucks without adequate performance or refinement»

Buran: The reduction in CO_2 emissions and reduced fuel consumption are two distinct advantages of HEV technology. However, the new Honda Accord i-CTDi engine offers results very close to that of current HEV performance. Which of these technology types do you think has the current advantage? Also, which technology has the greatest long term prospects?

AV: State-of-the-art diesels, like the Honda i-CTDi, currently have the advantage over HEVs in terms of cost and complexity, and in Europe high pressure direct injection diesels offer an option that is hard to beat. In gasoline based markets, such as the US, they are not popular because the public perception of diesels is very poor, and they are still associated with noisy, dirty trucks without adequate performance or refinement. Since diesel is not seen as a viable alternative to gasoline in these markets, the manufacturers are looking to hybrids to offer *the customer improved fuel consumption without having to persuade drivers to adopt a different engine technology.*

The obvious extension is to develop a diesel hybrid, particularly for the European market, but this will add weight and cost to the drivetrain. Since a diesel block is already heavier and more expensive than a gasoline engine, manufacturers will look to gasoline hybrids first, which is why I believe the HCCI/HEV research is so exciting.

Buran: How important do you consider the needs of the market / collaborators when defining the objectives of an HEV project?

AV: In any project, whether research or development, it is essential that the requirements of the stakeholders are considered at the outset. However, in defining a collaborative project you also need to consider that particularly industrial partners may face short-term commercial pressures that can detract from longer term strategic goals.

Also, 'the market' isn't a static, fixed set of conditions over which we have no control, but it is dynamic and can be influenced. It is important that not only is the market considered, but also how it might alter as technology is introduced, cost structures vary and legislation is changed.

Buran: How important do you consider the business case of HEVs to be? Have you ever considered putting together a business case for both the potential sales and movements of HEVs?

AV: It's essential. As a Project Manager in applied research, I'm continually reviewing the project plan against the business case, since without this it would be impossible to assess whether the project outcomes continue to justify the cost. In a research environment, the business case is wider than simply anticipated sales and margin, since there is also credit for the quality of the research undertaken.

We are putting together a detailed business case for HEVs including all these considerations, and also a much wider «what-if» analysis based on anticipated and potential changes to the external environment, such as new technology introduction and government intervention. This will be published in due course.

Buran: Could you please give an overview of current and future work with HEV research within PARDP (Premium Automotive Research & Development Programme) at the University of Warwick?

AV: We are working on two HEV projects at the moment – one is looking at the technology necessary to realise a successful hybrid powertrain, and as I've implied in my previous answers we're also looking at building a better business case to encourage hybrid introduction, looking at the political and socio-economic aspects that exist alongside the technological developments.

The research is part-funded by the Regional Development Agency, and we are collaborating with a number of local companies to develop a model that will allow us to simulate how locally produced components will perform in a hybrid powertrain. We can also 'scale up' the results to build a picture of the wider benefits that can be achieved for a number of external scenarios, such as a range of fuel prices or bands of taxation on CO_2 emissions. There's a better overview of the ongoing research on the projects' website, at www.iarc.warwick.ac.uk/8-hybrid-overview.html!

by John Poxon & Diego Sánchez Repila

INTERVIEW:
FRANCISCO TRINIDAD

«For the medium cars and Sport Utility Vehicles (SUVs), the technology of choice will be HEV»

Francisco Trinidad is a Doctor in Science, electrochemical major for the *Autonoma* University of *Madrid*. He started his professional career in *TUDOR* (1977), developing several research projects related to Zinc primary batteries and polymeric batteries. In 1986, he was designated Head of the Research Laboratory and subsequently in 1992 became Director of Industrial batteries development in *Madrid* and *Soet* (Germany); where he managed the development department of the *Hagen* company. In 1994, *EXIDE*, the first world battery manufacturer, acquires TUDOR and joined together with other French, German, Italian and British companies, to create the *EXIDE Holding Europe Group* (with social head office in Paris). He was the role of Development Director until 1996 and Research Director until 2002. Currently, he is the Director of Innovation in the Transport Division.

EXIDE Research

Buran: Could you please give a brief explanation of the research aims that EXIDE are currently involved with; particularly on the focus of systems storage in hybrid electric vehicle (HEV) applications?

Francisco Trinidad: EXIDE is one of world's largest manufacturers of lead-acid batteries and the R&D focus is in this technology, trying to improve performance (mainly specific power) and durability under partial state of charge conditions that are particularly relevant for HEV applications. The most recent innovation that we have introduced is the use of special graphite and micro-fibre glass in the negative active material of Valve-Regulated Lead-Acid (VRLA) batteries.

Hybrid Electric Vehicles (HEVs)

Buran: Why is lead-acid technology a good choice for HEVs? What are the current limitations of the technologies?

FT: In terms of cost of the energy or power needed for HEV functions lead-acid is the most favourable technology. However due to the high density of lead there is a limitation on the specific power as well as in terms of cycle life, still low as compared with other advanced technologies.

Buran: From a technical perspective,

which battery technology (Lead-acid, Nickel-cadmium, Nickel-metal Hydride and Lithium-Ion) would be best suited for the application of full HEVs, what are the overall advantages and disadvantages of this technology type?

FT: From the performance point of view, Lithium-ion is the most suitable for HEV because its combines a very high specific power with long life. However cost and safety are strong limitations, for that reason today's technology of choice is Nickel-Metal Hydride is spite of the high cost of the raw materials. Cadmium is not allowed for environmental reasons and lead-acid's power and durability are still not sufficient for full HEVs.

Buran: Currently on the market there are parallel configured HEVs of varying voltages. How do you choose the optimum voltage? What are the differences in capabilities in choosing different voltage outputs?

FT: That depends on the degree of hybridisation. Start/Stop and regenerative braking is possible at low voltages (14V/42V) but full electric power requires much higher voltages (>144V) to reduce ohmic losses.

Buran: What would you consider to be the most important factor to improve in batteries for HEVs? Are there any improvements which are crucial to the developments of HEVs growth?

FT: Specific power for acceleration, charge acceptance for regenerative braking and durability under partial state of charge conditions are the most critical battery issues for the development of HEVs.

Buran: Is the Battery Management System (BMS) of an HEV important? If so, why, and what are the capabilities of a BMS? What specific actions does the BMS require / produce?

«In terms of cost of the energy or power needed for HEV functions lead-acid is the most favourable technology»

FT: BMS is an integral part of the electrical system. It has to be able to determine precisely the state of charge, state of health and power capability (in charge and discharge) of the battery. Actions to be taken depends on the vehicle design and battery technology, the most common are related to thermal control and energy management.

Battery Requirements

Buran: Are there any new requirements for vehicles in terms of batteries? If so, what are they?

FT: In conventional vehicles, the battery is intended to start the engine and is almost fully charged all the time. In HEVs, the battery has to accept power from regenerative braking and should be able to launch the vehicle, even for a full acceleration period. As a consequence the most important requirements are specific power (end terms is W/kg) and energy (in Wh/kg) and last but not least durability under high rate partial state of charge conditions.

Buran: Which other measurements within HEVs are governed by the movements of legislation?

FT: Environmental legislation is the trigger for HEV application: Fuel consumption and emission reductions are being enforced by legislation, then batteries are an integral part of new legislation on vehicles emission.

«Nearly 100% of lead-acid batteries are recycled today»

Buran: What is the life-expectancy of the lead-acid technology? Would this battery technology be able to last the life of the full HEV, or would they need changing during the useful life of the vehicle?

FT: Life-expectancy would depend strongly on the amount of energy to be stored as well as the temperature, rate and state of charge. For full HEV the requirements today are not achieved by the state of the art lead-acid battery.

Buran: In the case of a crash, are the battery packs safe? If so, what measures have taken place to ensure the safety of both the driver and the battery packs?

FT: This depends on the technology: Lead-acid and Ni-MH are safe, but high temperature technologies (Na-S) were not considered safe enough in the past. Lithium safety is still a concern and should be proven in large scale applications.

Buran: When the vehicle comes to the end of its life, who is liable for the safe disposal of the battery packs? How is the disposal of the battery packs dealt with?

FT: There are special companies to deal with this environmental issue. Nearly 100% of lead-acid batteries are recycled today, but other technologies should develop further the recycling process to be economically viable.

Buran: Battery packs can either be designed with four connectors (2 anodes and 2 cathodes) or two. What would you consider to be the best option? Are there significant differences between either choice?

FT: Double connector reduces the electrical resistance and improves efficiency of the charge/discharge process. On the other hand, material and manufacturing cost are increased. For lead-acid technology this design is still in development and reliability needs to be improved.

Migration towards 42V

Buran: Is a 42V network power system safe enough to drive with?

FT: Yes, there are some mild hybrid vehicles in the market (Toyota crown, GM Silverado) with 42V network where safety problems have been overcome.

Buran: Does a 42V power system easily meet the power demands of the vehicle?

FT: The 42V network power is not intended for full power hybridisation, but for power assist (launching) and regenerative braking, that means around 10-20% of the total power needed for the vehicle.

Buran: According to Igor Demag (Peugeot and Citreon's hybrid vehicle developments), there is no significant connection between HEVs and 42V supplies. Do you agree?

FT: Yes, most car manufacturers are looking for high voltage HEVs (>144V), whereas 42V network is more considered for future high power demands on conventional vehicles.

Buran: According to E. Karden (Leading automotive engineer at the Ford Research Centre, Germany), the current 12V technologies are suffice, and states it is not necessary to move towards 42V systems for conventional vehicles. Do you have any views

on this matter? Why has this not taken affect as yet?

FT: Start/Stop applications are in the market with 12V batteries (Citroen C3, for instance), but regenerative braking is in the development phase because of the difficulty to accept charge at high rate in lead-acid batteries.

The Future: New Technologies

Buran: Is it possible to apply the technology of supercapacitors to vehicles today; including HEVs? If so, how can this be achieved / implemented? If not, what measures would need to be put into place in order for the operation of such a technology to take place?

FT: From the technical point of view, the combination of capacitors and lead-acid batteries is feasible because the power (and charge acceptance) of capacitors is superior to any battery technology, whereas lead-acid is the most economical energy storage system for automotive applications. However, in order to be economically viable, capacitors should reduce its price at least one order of magnitude.

Buran: What is your opinion of hydrogen fuel-cell technology? What are the current limitations, preventing it from being introduced?

FT: Fuel cell technology is not new; it was invented almost 2 centuries ago. The technology is still too expensive for automotive applications and will need further development to be a reality in high volume consumer or industrial applications.

Buran: Do you see HEVs as the transitional technology nearing towards the long term plan for fuel-cell operated vehicles?

FT: Yes, this can be a possibility, but the transitional period is going to be significantly larger than expected (10-20 years).

«The transitional period to fuel-cell is going to be significantly larger than expected (10-20 years)»

Buran: What other technologies do you think may progress in the future? Is HEV the best option?

FT: Electric vehicles (EVs) with Lithium batteries is a viable alternative for small urban vehicles, particularly some manufacturers in Europe and Japan are bidding for this technology. However, for the medium cars and SUVs, the technology of choice will be HEV due to the performance and range constraints of EVs.

Buran: What are the future possibilities for EXIDE in terms of HEV research?

FT: EXIDE is developing the ORBITAL VRLA Technology and will further improve durability in the present decade in order to offer the lowest cost alternative for HEV applications. We still believe that lead-acid technology will take a significant share of the HEV market because cost of energy per Km will still be the most important factor for car manufacturers.

by Diego Sánchez Repila & John Poxon

EL ABANDONO DE <<LIS ESTELES>>

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Las posibilidades de comunicación dictarán la sentencia. El próximo siglo -sería solemne en exceso decir milenio- asistirá a una convergencia de las culturas oriental y occidental. De estas imbricaciones lo que interesa es la fecundidad, esto es, la potencia que depare a la vida personal.

Si cultura es, como entendía Ortega, ese lugar donde podemos trasladar nuestras entrañas, entonces es claro que la primera misión de cada ser humano en ese camino será *identificarlas*, hacernos a la idea de que *nosotros somos alguien* y, por eso, *ellos*, los otros humanos, también.

El monje católico norteamericano Thomas Merton (1915-1968) escribió a propósito del sabio chino Chuan-Tzú que la vida en sociedad trae como secuela confundir nuestra existencia, pues nos lleva a obsesionarnos con lo que no somos y a olvidar *quiénes* somos realmente. Todo podría quedar como un mero juego de palabras si no especificásemos que «yo soy yo y mi circunstancia, y si no la salvo a ella no me salvo yo». El «yo», individual o social, no se salva si no se atiende a lo que nos rodea, siempre cambiante.

El hombre no tiene naturaleza, sino que tiene historia; es persona, es el animal que tiene vida humana, a pesar de que no la aproveche o de que sea tratado sin compasión. Los pueblos no tienen identidad, sino herencias con las que construir el futuro. *Nada humano me es ajeno* es el lema de todo pueblo que sabe prolongarse.

Con un punto de sosiego, y curándonos de la ansiedad que nos abruma, podríamos advertir que «todo el cosmos es un grano de arroz, y la punta de un cabello es grande como una montaña». Una sentencia con *sabor oriental* pero compatible con el estilo occidental, así nuestro poeta Maragall decía creer que «el hombre más sabio del mundo es aquel cuyos ojos, habiendo visto mucho, conservan del todo la visión del niño de antes de ir a la escuela». De este modo, acabamos por cruzarnos con la música del lenguaje y la mística.

El propio Maragall escribió a principios del siglo XX un artículo de prensa profundamente personal y que merece ser leído íntegramente, «Las lenguas francas», en donde busca *la niñez fermentada de las lenguas*, esto es, en clave orteguiana, su poesía. Habla Juan Maragall (así se firmaba cuando escribía en castellano) de su enamoramiento de las variantes múltiples y encantadoras de un mismo lenguaje áspero y dulce, *libremente matizado*. Camino del pueblo gascón de Gavarnie en la oscuridad de la noche, nos cuenta que acercándose a Gedre, «pueblecillo que lleva un nombre bonito» surgió «como una pequeña hada, una niña de cinco o seis años, pidiendo limosna -¿podíamos negársela?-. La hicimos hablar por el gusto de oírla. -¿Cómo llamas tú a las estrellas? -le preguntamos (a aquellas alturas sólo se ocurre nombrar cosas grandes y maravillosas). -*Lis esteles* -contestó con su vocecilla de hada en el infinito silencio. *¡Lis esteles!* Alzamos los ojos al cielo y las estrellas nos parecieron brillar con nueva luz del inmortal misterio». Y explica que la dulce libertad del verbo pirenaico le penetró deliciosamente en el hondón del alma.

Concluye exclamando: «¡Cómo quisiera meter este sentimiento en las entrañas de nuestros hermanos pirenaicos que desprecian su *patois* (*patois*, pero suyo) por la hermosa lengua de Racine (hermosa, pero de Racine)!» Es el orgullo de una lengua *secundaria* que se defiende de toda ideología por *propia* que sea; con presión oficial y chantaje afectivo hay en la España de hoy casos de domesticación y sometimiento mediante la lengua, de este modo se estrangula el pensamiento, la expresión libremente matizada.

Unamuno, entrañable amigo del escritor catalán, pedía oír en el silencio los ecos dulces de la niñez lejana como rumor de aguas frescas y vivas, esto es, con afán de recuperar el tiempo pasado. Pero «¡Santa sencillez! Una vez perdida no se recobra», confiesa en su *Diario Intimo* (publicado por primera vez en 1970). No obstante, creyendo que hay que vivir con toda el alma, se propone vivir en adelante «obsesionado en salvar mi alma».

Demasiado anunciado, ¿a quién le seduce el plan del medieval místico alemán que recomendaba: «Acuéstate a la noche como si fuesen a enterrarte a la mañana, y levántate por la mañana como si hubieran de enterrarte a la noche»? ¿Quién lo podría soportar siguiendo el consejo de forma literal? Otra cosa es sentenciar: «Cuanto más vivas en Dios más en tí mismo vivirás, más dentro de tí mismo, y serás más tú». Hay en las páginas de esos cuadernos de Miguel de Unamuno dos frases, en particular, que resultan hoy día insólitas por su franqueza y decencia. En la primera, el escritor vasco, despierto de su vanidad, afirma: «He vivido soñando en dejar un nombre». Claro está que esto no es negativo en sí mismo, salvo que nos reduzca la autenticidad personal. Por su parte, la segunda frase es un diagnóstico singular, de valor imperecedero: «Estoy muy enfermo, y enfermo de yoismo».

Para sobreponerse de esa caída hay que seguir una ruta de soledad, donde lo importante no es llegar primero sino saber llegar para *volver a vivir*. La cultura no sería entonces el lugar o la posada donde podemos trasladar nuestras entrañas, sino el zurrón que llevamos en nuestro itinerario íntimo: una bolsa con poco peso al costado de quien está dispuesto a quemar las naves fantasmas de la vanidad y llegar a puerto para bañarse como náufrago de la vida. Algebra de estas metáforas es Compostela, hacía ella conduce por los campos, peregrinando, un recorrido mágico y magnético. El camino alfombrado de estrellas se *inauguró* con las debidas licencias eclesiásticas en el siglo IX, pocos años después de que un ermitaño observara una lluvia de estrellas y la asociara con el anuncio divino del oculto sepulcro del apóstol Santiago. Hoy día, el camino de los peregrinos, nombre específico de los que se dirigen a la localidad gallega para acabar dando un abrazo al busto del hijo del Zebedeo, está de moda. Las razones de tal peregrinaje han evolucionado con los siglos, pero ahora ¿qué se busca con esa marcha?

«Deportivamente» se aproxima a las tan concurridas carreras pedestres por las urbes, pues de lo que se trata es de participar y llegar a la meta en ambiente masivo de fiesta. Pero en este caso aparece un componente religioso intermitente. Se sea creyente en Cristo -con mayor o menor fervor, con mayor o menor coherencia- o no se sea, se acaba el *juego* llegando con gozo al adorado templo. Muchos evadidos de las ciudades, acaso con más de un desespero a cuestas, buscan renovarse, sentirse capaces de alguna gesta reconocida, huyen de la anomia de las ciudades, cuyas luces deslumbrantes impiden *ver*. Sin embargo volverán a *casa* con indefinible saudade al finalizar su visita por esos terrenos, semejantes a los ocupados hasta no hace mucho por sus antepasados rurales, y que han hecho suyos con su andar. La presencia patente y benigna de la historia fortalece el deseo.

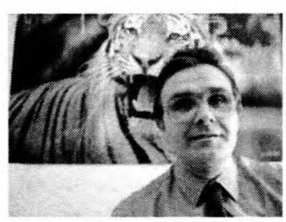
Es evidente que sólo el tiempo libre nos ha permitido seguir *el camino*, un camino también ruta de comunicación social y económica. Y aquí nos encontramos con las entreveradas razones líricas del ser humano. Lo más hondamente interesante que hace un hombre con su vida no es para hacer negocio. Por eso conviene reivindicar el ocio como tiempo personal, reconquistarlo de su imagen más engañosa, el cebo de un negocio organizado con ávidos buscadores de dinero y placer.

Maragall se refirió lúcidamente al ocio como «la condición indispensable de ciertos descubrimientos científicos y de la producción poética, artística. La condenación del ocio conduciría a resultados desastrosos. Porque ocio se llama, por ejemplo, la conversación y la lectura; y, sin embargo, una y otra son las que forman principalmente la opinión y las costumbres». El ocio nos permite así el tránsito de la holganza a la holgura en la vida. Con sosiego siempre podemos *reconsiderar* las cosas y las personas, el quehacer vital.

Nunca acaban de desaparecer las estrellas, tarde o temprano reaparecen. Pero no podemos quedar prendidos de por vida a una hoja, analógica o digital, examinando el anuncio de la hora afortunada, los horóscopos que dan la nota de los vividores. Ansiosos de forma crónica por el espectáculo universal, hemos celebrado hace pocos días que el Sol abandonase la escena y desertase de su papel. Esto significa el término de origen griego eclipse: deserción, abandono, desaparición. La mayoría ha asistido al evento con atropellado y frustrante jolgorio; otros han confiado en el desastre final. Entre aquellos ha sido inevitable para algunos sentir la «injusticia cósmica» de la distribución del oscurecimiento solar; en España, la capital menos *afortunada* fue, según leo, Las Palmas de Gran Canaria, con un 23 por ciento, mientras que San Sebastián y Santander encabezaron la lista con un 78 por ciento. Ha habido asimismo pueblos enteros de la Tierra que, dominados por la ignorancia e inconscientes del saber científico, han tomado al pie de la letra sus mitologías.

Aunque estemos a años luz de la comprensión de la mecánica celeste y de la ciencia astronómica, ¿cómo podemos suplantarla? En su camino por la vida el hombre ha de saber arrastrar su *sombra lunar*, sus carencias y deficiencias. Desde ese *saber no saber*, no abandonará su guía, a veces invisible, de «lis esteles».

AUTOR



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OMAR: CÓNICAS Y VINO

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Las cónicas y el vino también pueden rimar juntos. Nosotros, por nuestra profesión, siempre estamos dispuestos a sorprendernos. Por ejemplo, hay un contribuidor de la matemática que nació aproximadamente cuando el Mío Cid, a mitad del siglo XI. Era persa y natural de la ciudad Nishapur. En unas enciclopedias lo encuentro denominado Omar Khayyam y en otros libros como 'Omar Jayyam' (es el caso del libro del profesor Ricardo Moreno, del cual he conseguido información para estas páginas). Sin buscar fundamento filológico le llamaremos aquí Khayyam, nombre que según tengo entendido significa constructor de tiendas. De hecho, actualmente Omar consta básicamente como constructor de poesía. Citemos dos versos: «Antes de que tu nombre en el mundo se borre/ bebe vino, que el vino alegra el corazón». Hay que decir que Khayyam pertenecía al mundo musulmán, lo cual puede explicar que esta dimensión poética no fuese conocida hasta dos siglos después de morir. La vida, ciertamente, da muchas vueltas. Sus poemas fueron transmitidos a Occidente (y de paso al propio Oriente) por Edward FitzGerald (sí, tal cual, con g mayúscula). Este señor inglés, nacido el mismo año que Darwin (1809) publicó en 1859 (también el año que salió 'El origen de las especies') su traducción de unas poesías orientales que había encontrado en una biblioteca. Sin embargo no tuvo resonancia hasta que dos influyentes lectores dieron razón de su importancia.

Omar ideó una forma de 'cuartetas' caracterizadas por la falta de rima en la tercera línea, se llamaban 'Rubaiyat'. Ocho siglos después su camino se prolongó gracias a la acción de FitzGerald. Su traducción era libre, algo que ya había hecho con Calderón de la Barca (un autor, por cierto, muy querido por muchos y destacados autores alemanes e ingleses). Se ha llegado a decir que su trabajo fue una verdadera 'transfusión poética' y que no solo transmitió con acierto la esencia de su estilo y pensamiento si no que lo rescató de un eviterno olvido. Hay que decir que Rubén Darío llegó a escribir un prólogo a su versión en español. Y también que Jorge Luis Borges redactó en 1969 un poema con el mismo título y con la misma técnica, está incluido en 'El elogio de la sombra'.

Además, Khayyar no fue sólo un poeta, por eso lo tenemos aquí, en estas páginas. Fue un matemático y un astrónomo de renombre, que tenía como libros de cabecera «Los elementos», de Euclides y «Las cónicas», de Apolonio. Escribió unos interesantes 'Comentarios sobre aspectos dudosos en los postulados del libro de Euclides', que giran alrededor del verdadero debate sobre el quinto postulado de Euclides, clave de las geometrías no euclídeas. Hay que citar también sus brillantes e ingeniosas resoluciones de ecuaciones cúbicas cortando cónicas (las cuales, recordémoslo, son curvas de intersección de un plano y un cono). No puede pasarse por alto que el álgebra es históricamente el terreno matemático mejor labrado por los árabes.

El sultán Malik Sha, muerto en 1092, lo convocó para emprender las observaciones astronómicas precises para la reforma del calendario. Así, se abandonó el año solar persa (que ellos nos transmitieron) por el lunar musulmán. Este último se caracteriza por contar un mes al acabar las cuatro fases de la Luna.

Leo esta sentencia con la que Omar cerraba sus libros: «Alabado sea Dios en toda circunstancia y bendito sea Mahoma (la mejor de Sus criaturas) y su familia buena y virtuosa. Con Dios nos basta, ¡qué gran Protector es!». Por último, tengo delante un retrato suyo; no recuerdo ninguno del Mío Cid, a pesar de que hay esculturas suyas, como la que hay en Valencia, ciudad que reconquistó. Veo una frente amplia, la cabeza cubierta por un turbante claro que deja al descubierto su oreja derecha, unos ojos penetrantes con una mirada tranquila, bigote y barba canosos. Es el rostro de quien escribió «Al período en el cual llegamos y partimos/ ni se le ve el comienzo ni el fin se le vislumbra/ y no hay nadie que pueda decirnos de verdad/ de dónde procedemos ni a dónde partiremos». Se trata de uno de los hombres de quienes puede decirse que está en la torre de nuestros conocimientos anónimos, desde sus hombros asomamos para divisar un horizonte.