

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 CO₂ 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 Electric 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.

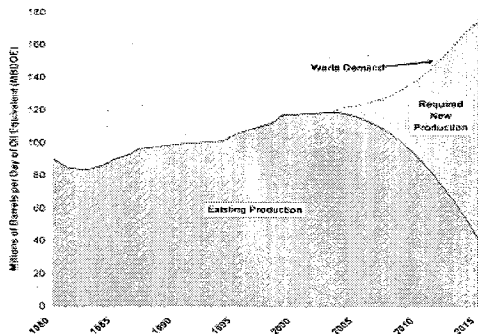


Figure 1: Gas and Petrol Provisions (Source: Exxon Mobil 2004).

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 overlooked. 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 13 km/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 CO₂ emissions from vehicles. In fact, CO₂ is the primary greenhouse gas

which increases global temperature. The emissions of CO₂ 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 CO₂ from vehicle transport represent 48% of the overall amount of CO₂ 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 CO₂.

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

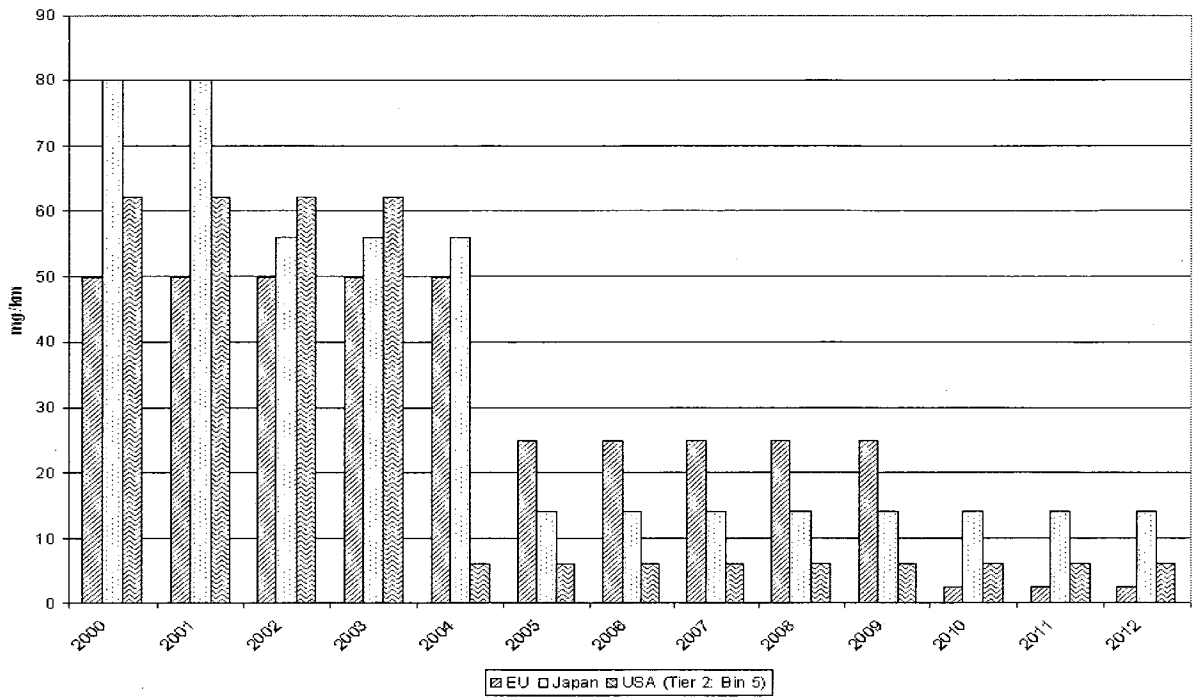


Figure 2a: CO₂ Emissions Limit Forecasts

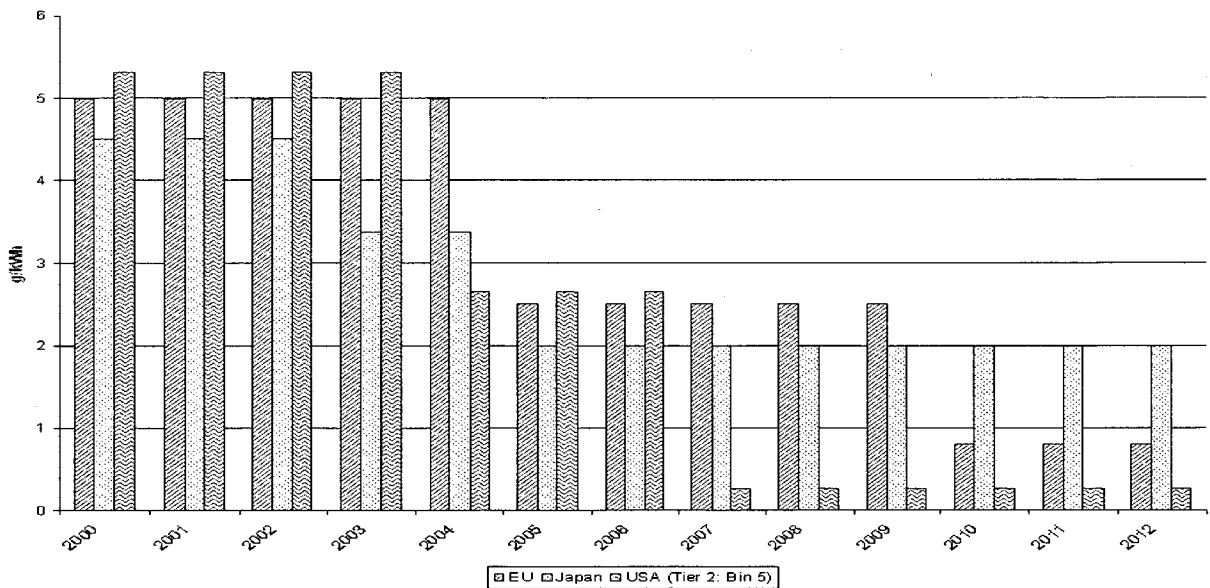


Figure 2b: NO_x Emissions Limit Forecasts

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

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 CO₂

emissions to 140 g/Km by 2008, and reduce these still further to 120 g/Km by 2012. The current average levels of CO₂ 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 Electrical Engineers (IEE), 2001.

4.3. Conclusion

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 CO₂ emissions. Even experts have forecasted a number of new diseases provoked by the high concentration of CO₂ [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.

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 current 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 overtime 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 their 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:

$$F = m a \quad (1)$$

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 its 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 valvetiming, 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

the energy generated during the braking cycle is recovered for storage in the batteries.

The IMA in the *Honda Insight* boasts 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 its 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

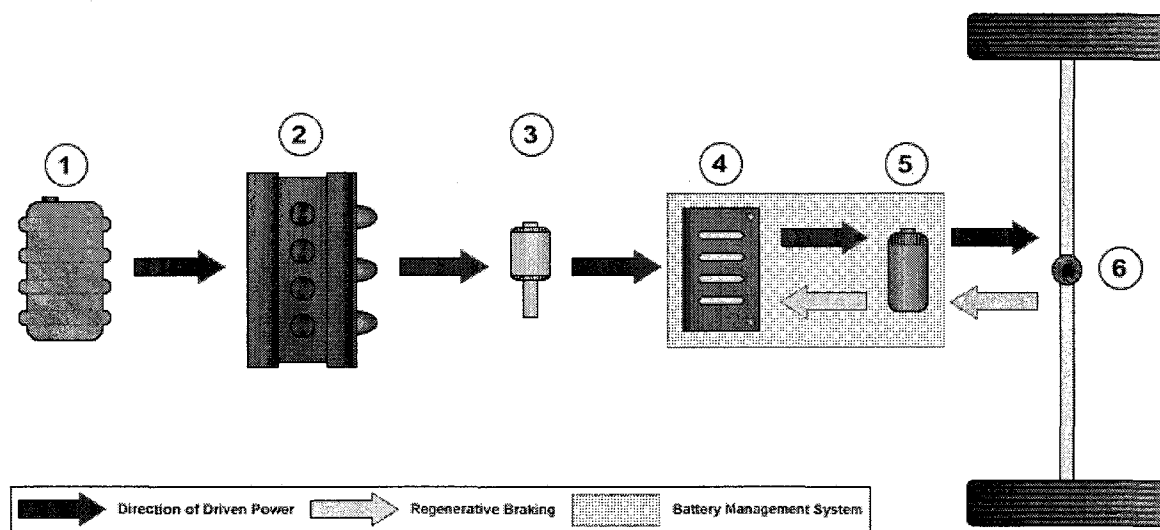


Figure 3: Series Configured HEV

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 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].

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

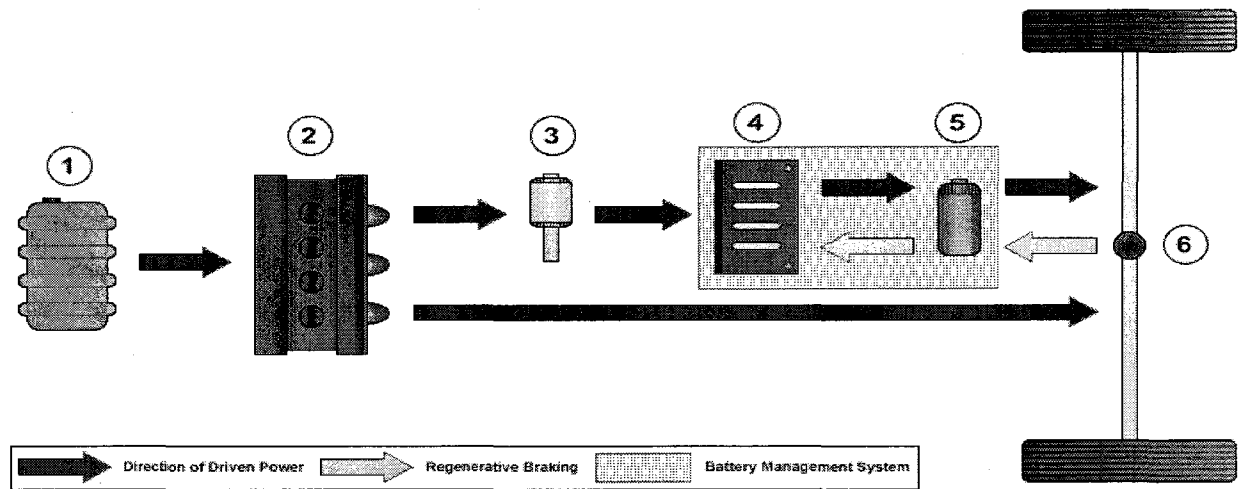


Figure 4: Parallel Configured HEV

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.

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.

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.

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.

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

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

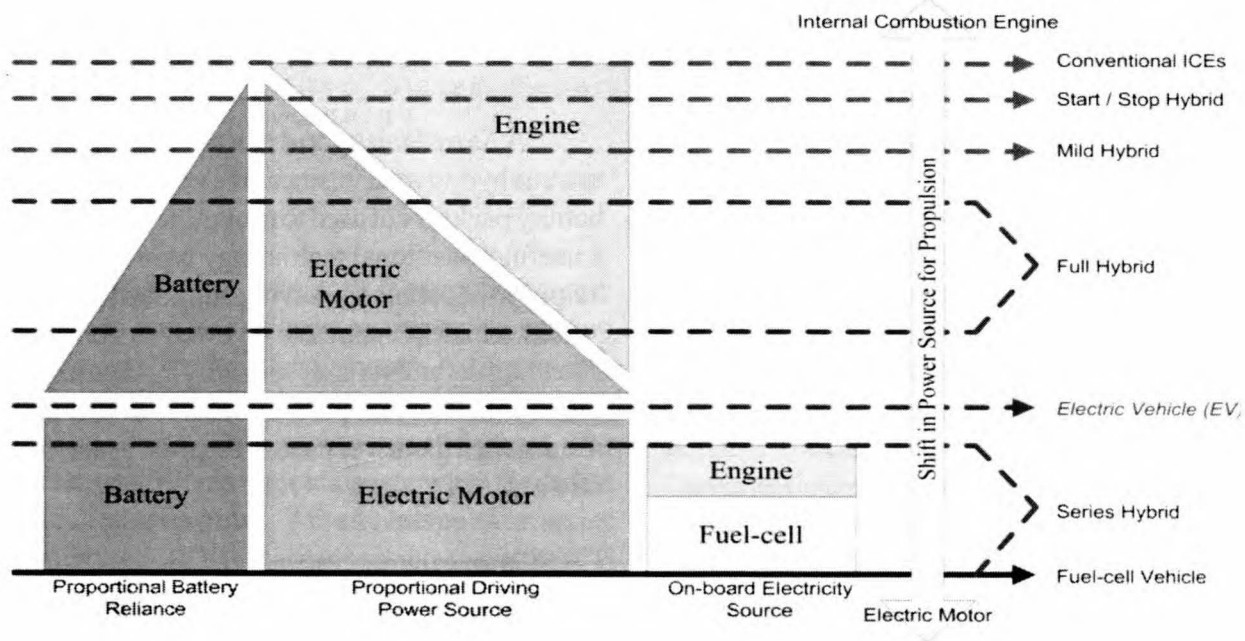


Figure 5: Hybrid Types and Configurations

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	-	-	-
SUVs / Minivans	Chevrolet	Malibu	2007	-	-	-
	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* boasts 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 accepting 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.

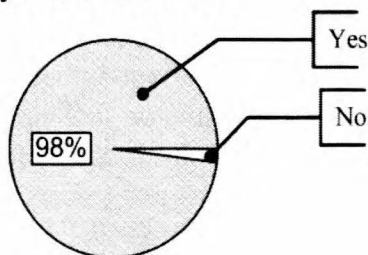
9.2. USA Market

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]. Undoubtedly, looking at figure 6 it is clear to see that this market along with the Japanese has the most potential riding on it.

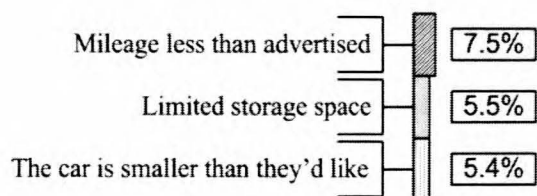
9.3. Japanese Market

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

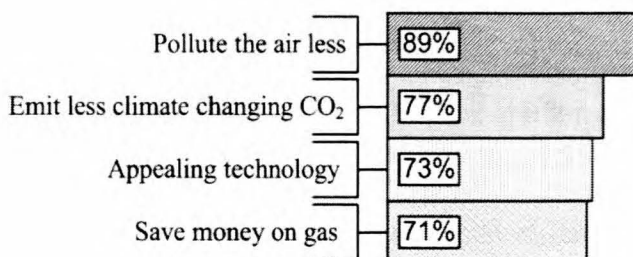
Would you recommend your hybrid to a friend?



What do you like least?



Reasons you bought a hybrid?



What do you like best?

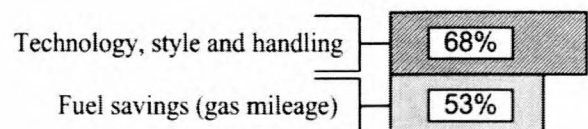


Figure 7: Hybrid Drivers Survey (Source: Oregon Environmental Council 2003)

the forecast 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

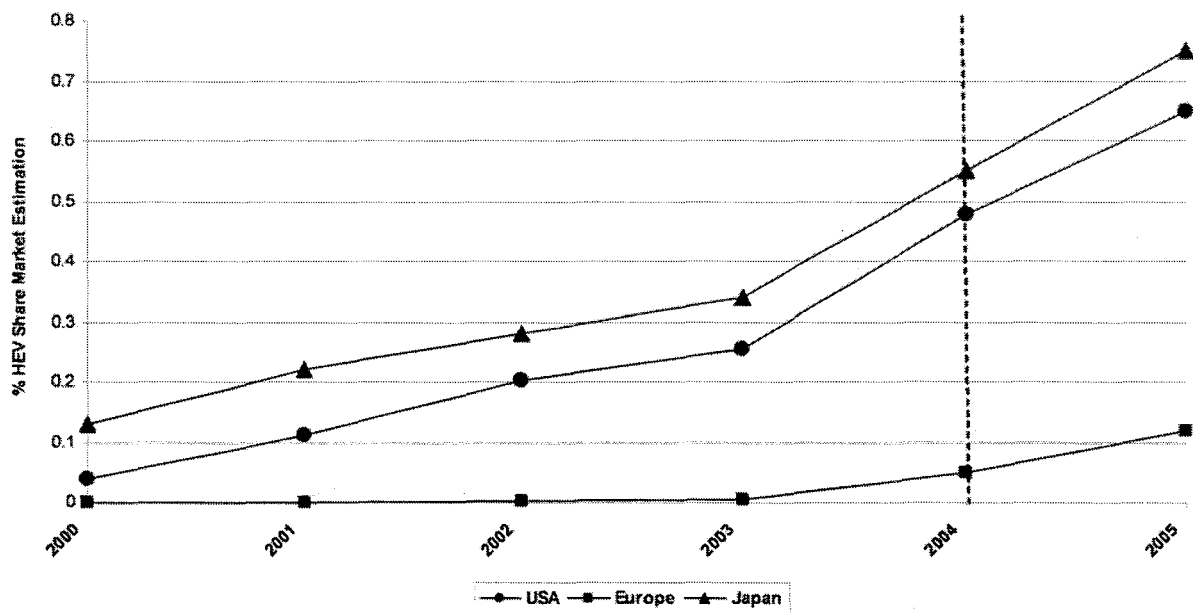


Figure 6: HEV share and market estimation

inclusion and development of biodiesel. Over the lifetime 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 CO₂, 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 CO₂ emissions is equivalent to the decrease in fuel consumption. (CO₂↑ => km^l⁻¹ ↓).

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.

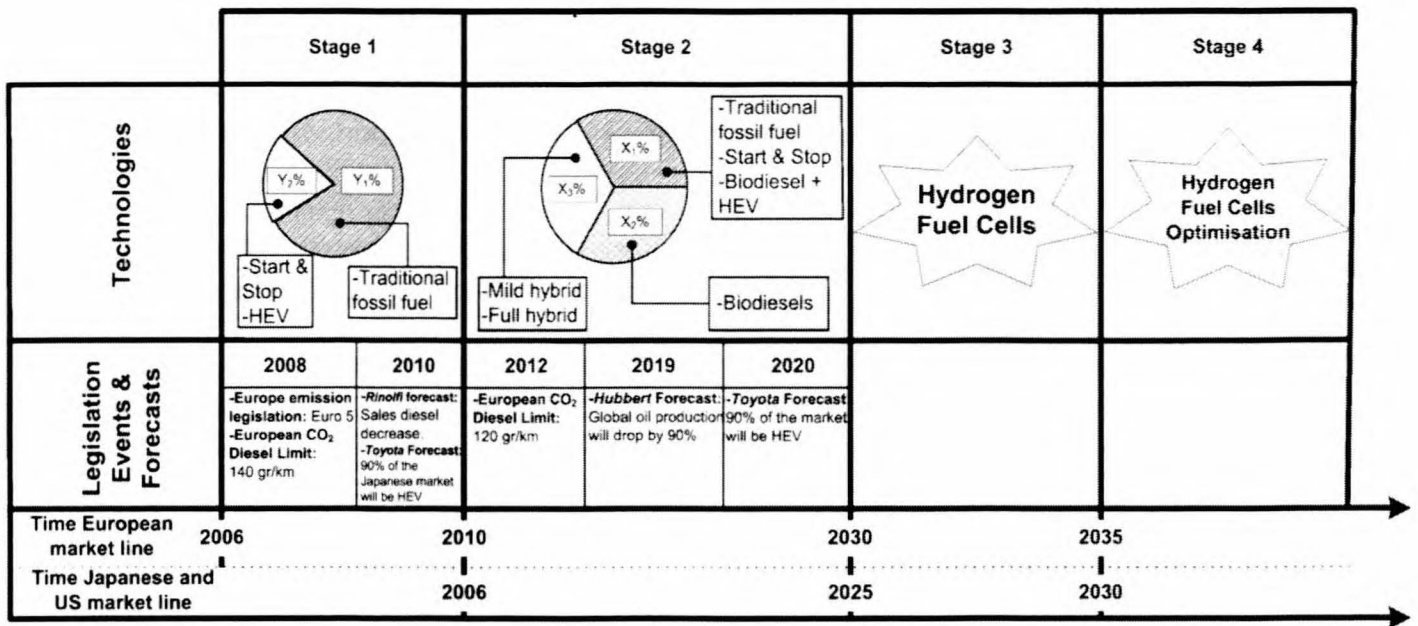


Figure 8: Fuel Future Trends Estimation based on important forecasts.

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 CO₂ 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 ($Y_1\% \gg Y_2\%$).

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 CO₂ 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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