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Hybrid light vehicles:
technologies and trends to 2015

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INTRODUCTION

Because electric vehicles preceded those powered by an internal combustion engine (ICE), vehicles with hybrid drivetrains that combined an ICE with electric propulsion were produced shortly after the advent of the ICE. However, the rapid development of the ICE made the need for additional power of an electric motor redundant and the technology was largely overlooked until petroleum fuel prices became an issue with the first OPEC oil shocks of the 1970s.

Various research projects followed but it was not until Audi and Toyota launched hybrid models into the market in 1997 that the modern ICE-electric hybrid arrived. The Audi was not a success, but the Toyota Prius remains the leading model in a rapidly growing market niche. To date, global hybrid market growth has been dramatic with around 25 models launched by the end of 2007 and a compounding annual sales growth rate of almost 70% during the last five years.

Although an ICE and an electric propulsion system can be configured in several different ways, light passenger hybrids have so far been of 'parallel' or combined 'parallel/series' configurations in which both the ICE and the electric drive can directly power the driving wheels. However, 'series' hybrids, in which the ICE simply drives a generator to power the battery in what is otherwise an electric vehicle, appear to have a strong future as consumer interest in the fuel economy of electrically-powered propulsion builds.

As governments and consumers become increasingly concerned about petroleum fuel consumption and carbon dioxide (CO2) emissions, hybrid technology presents an appealing route because it can reduce a vehicle's fuel consumption by as much as 25%. This has led some governments to support the hybrid market by offering incentives and tax structures that favour hybrids and other low-emissions vehicles.

Working against the widespread adoption of hybrid vehicles, however, is the matter of cost. The technology adds a considerable number of components to the drivetrain and its management systems, and batteries, in particular, account for a major slice of the incremental cost accompanied by the prospect of an expensive refit at some point. Because of this, consumers in several countries, most notably in Europe, clearly prefer diesel-powered vehicles, which can offer almost the same fuel economy benefits over a gasoline-powered equivalent and carry a substantially lower purchase price premium.

Given that the underlying issue is that of fuel efficiency, it seemed natural that the first three hybrids in the market were compact cars with downsized ICEs complemented by an electric motor and a battery pack. However, profit margins are slim in the smaller car segments and consumers have consistently demonstrated that there is a strong demand for SUVs and other larger vehicles so it is perhaps no surprise that ten of the around 40 hybrid models (if those that essentially differ only in brand badges are counted as one model) that are currently in or destined for the market by 2010 are SUVs, six are MPVs, two are full-size luxury sedans and two are full-size pick-ups.

Although other propulsion systems including hydraulic, kinetic and pneumatic drives have been combined with an ICE to create a hybrid drivetrain, so far those technologies remain marginal. This report focuses on ICE-electric hybrid light vehicles, to which the term 'hybrid' refers throughout.

Also, although hybrid technology is ideally suited to urban heavy commercial vehicle applications, and probably has a strong future in the urban bus and delivery truck segments, the scope of this report extends to cover only light vehicle hybrids.

HISTORY

The history of the hybrid electric vehicle dates back almost as far as the ICE-powered vehicle. Battery-powered electric vehicles preceded the automotive ICE by nearly 50 years but battery technology delayed commercial success until the 1890s.

Jacob Lohner & Company produced electric cars in Vienna from 1898 to 1906 and in 1899, Ferdinand Porsche, one of Lohner's employees, developed a series hybrid drive system that used an ICE to drive a generator that both charged a battery and powered electric motors in the front wheel hubs. When fully charged, it had a range of nearly 40 miles.

Figure 1: Early Lohner-Porsche

Source: Porsche AG

In 1900, Pieper, a Belgian manufacturer, produced a parallel hybrid car in which the 3.5hp (2.6kW) ICE and electric motor were coupled so that the electric motor could provide extra power when required. When not required for propulsion, the electric motor operated as a generator to charge the battery. Although several manufacturers produced hybrid vehicles up until around 1918, cheap petroleum and the mass production of the ICE sidelined further development of the technology until concerns about fuel efficiency gained prominence following the 1973 oil crisis.

In 1976, the US Congress enacted the Electric and Hybrid Vehicle Research Development and Demonstration Act to encourage the development of electric and hybrid vehicles. General Electric received support to develop a parallel hybrid passenger car and Toyota produced a series hybrid sports car that used a gas turbine engine and generator to power an electric drivetrain. Various other hybrids were built and tested during the 1970s, but interest in the technology waned as oil prices fell.

Audi picked up the challenge again in 1989 and produced the experimental 'Duo' hybrid based on the 100 Avant Quattro. The Duo supplemented the 100 Avant's 136hp (101kW) front-wheel drive ICE with a 12.6hp (9.4kW) electric motor driving the rear wheels and a nickel-cadmium battery. In 1997, the company launched the production of another Duo model based on the A4 Avant that used a 90hp (67kW) turbo diesel engine and a 29hp (22kW) electric motor that both drove the front wheels, and a lead-gel battery. It was not a commercial success.

In 1993, the Clinton administration in the US launched the Partnership for a New Generation of Vehicles (PGNV) which resulted in three hybrid prototypes all of which were capable of between 72mpg and 80mpg (US gallon). Toyota was excluded from PGNV and launched a secret development programme of its own that resulted in the launch of the Prius sedan and a hybrid bus in the Japanese market in 1997. The company's Crown and Estima hybrid models followed in 2001.

In 1999, Honda produced the Insight and immediately launched it in the US. Toyota took the Prius to the US market in 2000 and Honda followed with the Civic Hybrid in 2002. In 2004, using technology licensed from Toyota, Ford launched the first US-manufactured hybrid, the Ford Escape Hybrid SUV.

Chapter 1: Market drivers

MARKET DRIVERS

The rapidly-growing hybrid market is being driven by several factors including the pursuit of improved fuel efficiency, government and corporate incentives, particularly in the US, and the appeal to consumers and automotive manufacturers of making a 'green' statement.

Fuel efficiency

The huge increases in petroleum fuel prices during the last few years have resulted in widespread interest in improving fuel efficiency. Consumers want to reduce household and business expenses and governments want to reduce dependence on imported oil products and implement commitments to reduce CO2 emissions, such as those made through the Kyoto Protocol agreement.

As a consequence, the governments in the three major vehicle manufacturing regions have been working towards establishing future limits for average fuel efficiency:

- The EU has proposed that, by 2012, the CO2 emissions of each OEM's new vehicle range must average 130 grammes of CO2 per kilometre (g/km), 10g/km of which can be achieved by measures other than improved engine efficiency, such as improved transmission efficiency and low-resistance tyres. The current European average is around 160g/km.
- In Japan, the relevant government ministries have proposed an increase of 23.5% over the 2004 standards by 2015, from 13.6km/litre (32mpg US) to 16.8km/litre (39.5mpg US).
- The US Corporate Average Fuel Efficiency (CAFE) rules have been revised, effectively for the first time in more than two decades, with a proposed 40% improvement in fuel efficiency targeted for 2020. This will take the passenger car average from the current 27.5mpg (US gallon) and the pick-up and SUV average from 22.5mpg to a combined average of 35mpg.

Automotive manufacturers in the EU and the US have protested that the proposed goals are unattainable but supporters of the measures have pointed out that many vehicle models and some OEMs can already comply, and that the goals are achievable provided there is a general shift by consumers to smaller, more fuel-efficient vehicles. There are already some signs in the market that such a shift has already begun and forecasts that oil prices will continue to rise as demand increases and supply peaks could well give impetus to this trend.

Clearly, hybrid technology can assist by improving the fuel efficiency of vehicles in every market segment and market research indicates that fuel economy is the leading factor for consumers who purchase a hybrid. The fuel economy gains claimed by the various OEMs that market them range from 10% - 15% for mild hybrids through to 20% - 30% for full hybrids. Claims for city driving conditions, where hybrids are at their best, range from 40% to 58%, although in some cases the claimed savings have been achieved through the combination of cylinder deactivation and hybrid technologies, particularly in the large, V8-powered US SUV hybrids.

Incentives

Hybrids, along with alternative fuel and other low emissions vehicles, are eligible for various tax incentives, purchase rebates, parking discounts and the use of high-occupancy traffic lanes in some localities.

In the US, federal income tax credits of as much as US$3,000 are available to purchasers of hybrids, although they are structured to phase out once a particular OEM has sold 60,000 hybrid vehicles in the US and the current scheme will cease at the end of 2010. Toyota hybrids, including Lexus models, exceeded the 60,000 sales mark during 2006 and ceased to attract federal tax incentives from October 2007.

In addition, some state governments offer tax rebates or credits and discounted annual licence fees for hybrids and other low emissions vehicles. These have ranged from US$300 in Maine through to US$4,713 in Colorado. Further,

several cities offer low emissions vehicles free or discounted parking and allow them to use high-occupancy traffic lanes when carrying only the driver. However, several larger hybrids do not qualify as low emissions vehicles and are not eligible for these advantages.

The fuel economy gains claimed by the various OEMs that market them range from 10% - 15% for mild hybrids through to 20% - 30% for full hybrids

Some corporations in the US also offer incentives to employees who purchase a hybrid, including substantial financial assistance, free or discounted parking and increased vehicle allowances. Some US businesses offer discounts and parking incentives to hybrid owners.

In Europe, there is currently a trend towards structuring purchase taxes and annual licence fees in favour of vehicles with higher fuel economy. French OEMs receive government assistance towards the development of hybrids and purchasers are eligible for tax incentives of up to €2,000. Cities that have introduced congestion charges, such as London and Milan, structure the charges in favour of low emissions vehicles.

In Japan, purchasers of hybrid vehicles are eligible for a subsidy of up to half of the difference in price between the hybrid and its non-hybrid equivalent. This typically amounts to around 10% of the purchase price of a Toyota Prius or a Honda Civic Hybrid.

In China, the government has recently announced that hybrids will receive incentives, from production through to ownership, so that they will be less expensive to own and operate than conventional cars.

Green image

The wish to present an environmentally-concerned image appears to be a factor driving some of the growth in the hybrid market. The Toyota Prius has consistently outsold all other hybrid models and its sales in the US equal all other hybrids combined. Most significantly, it outsells its closest rival, the Honda Civic Hybrid, by at least 350%. Some of this could be because the Prius is a full hybrid that returns better fuel economy than the Civic mild hybrid, but some analysts believe it is because the Prius is a designated hybrid model with no direct non-hybrid equivalent. It has its own distinct style and can readily be identified as a hybrid, whereas the Civic Hybrid, apart from badges, is identical to the non-hybrid models.

OEMs are also aware that marketing a hybrid lends them ‘green’ credentials, as well as offering the perception to consumers that they have the technical capability to develop and manufacture high-tech products. GM, for example, has stated that it does not expect the first few years of hybrid production to be profitable, but recognised that it had to join the trend in order to maintain credibility. Ford has indicated that it has lost around US$3,200 on each hybrid sold since it launched the Escape/Mariner hybrid SUV in 2004 but claims that it has reduced the cost of its next-generation hybrid systems for the forthcoming Ford Fusion/Mercury Milan hybrid by 30%.

Chapter 2: Market barriers

MARKET BARRIERS

The cost of hybrid technology is a barrier to growth of the hybrid market and there has been considerable publicity regarding owners' disappointment with actual fuel economy gains. Also, the calculated payback periods required for fuel savings to offset purchase price premiums are generally longer than most consumers would welcome and the competition from diesels that appears to have limited the hybrid market in Europe is now beginning to make inroads in the US. Furthermore, while hybrids have proven to be as reliable as non-hybrids, the expensive battery packs will require replacement, or at least refurbishment, at some point.

Ironically, stop-start technology, which is used in all hybrid systems, could limit the growth of hybrid vehicles. Stop-start functionality can be achieved by installing components that cost no more than those they replace and can return worthwhile fuel savings in city traffic conditions.

Purchase price premium

The most significant barrier operating in the hybrid market is the premium that the technology adds to the purchase price. Consumer research in the EU, the US and Asia indicates that consumers are willing to pay a premium of up to 15% provided they can achieve a 50% improvement in fuel economy, which is currently beyond all hybrids in combined driving cycle conditions.

When the high premiums on luxury and SUV hybrids in the US are taken into account, the average hybrid price premium is around US$5,000 so it is significant that Honda has announced that it plans to produce an "affordable" hybrid that costs less than US$2,000 more than its non-hybrid equivalent. In the US, a Civic Hybrid costs around US$3,000 (16%) more than the 1.8-litre EX model non-hybrid with similar specifications. In the UK, it costs around £2,500 (18%) more than the 1.8-litre non-hybrid.

Real fuel economy

Many US hybrid owners have expressed disappointment during recent years about the actual fuel economy their vehicles achieve. To some degree, this has been because the US EPA fuel economy figures, which are determined through a set of dynamometer test cycles, have always tended to be optimistic when compared to actual returns but have inflated the estimates for hybrids even more than the estimates for non-hybrids.

From the 2008 model year, the EPA has added a further three test cycles to simulate high speed driving, aggressive acceleration, air conditioning use and driving in cold temperatures. As a consequence, estimates for the combined driving cycle have dropped by around 10%, although some have dropped by more than 25%. The estimates for twelve hybrid models available in the US dropped by an average of 12.5%, although those for the Prius and Civic Hybrid are now 16% and 18% respectively below the old values, bringing them closer to real world figures.

Long term test data published in the US by Consumer Guide and Consumer Reports during 2006 found that the fuel economy of hybrids under the old EPA testing regime was, on average, around 17% lower than the EPA estimates, with the Lexus RX 400h 26% lower, the Prius and the Civic 24% down and the Camry 20%. By comparison, in sample of 14 non-hybrids, the average fuel economy was only 1.5% lower than EPA figures, and ranged from 11% lower to 9% higher. Most significantly, the EPA city cycle estimates for hybrids were far higher than those found in real driving, whereas highway figures were relatively close.

The revised EPA estimates might go some way towards improving this situation although it appears that the difference for hybrids is still likely be greater than for non-hybrids given the similar average adjustments reported.

Premium payback

Given that most initial purchasers keep a vehicle for 3-5 years, purchasing a hybrid can only make economic sense if the fuel savings achieved during that period will at least pay back the price premium. However, even with the increases in fuel prices of the last few years, the payback time is still, in most cases, much longer than the average first ownership period.

Given that most initial purchasers keep a vehicle for 3-5 years, purchasing a hybrid can only make economic sense if the fuel savings achieved during that period will at least pay back the price premium

Edmunds.com has published calculations during the last two years regarding payback periods within the US based on the purchase premiums with allowances for federal incentives, and fuel cost savings based on average annual US mileage of 15,000 miles, fuel price at the time and the then optimistic EPA fuel economy estimates that will have skewed the calculations towards shortening the estimated payback period. In August 2006, when gasoline averaged US$3.00 per gallon and the Toyota Prius still attracted a US$3,150 federal tax incentive, Edmunds found that it had a payback period of 2.1 years if compared to the larger Camry but a daunting 13.6 years if compared to a smaller Corolla LE. With federal incentives now expired for Toyota, these payback periods will be substantially longer.

Of the other ten hybrids in the study, the Ford Escape was the only one, at 2.9 years, with a payback period of less than five years. The Saturn Vue and Honda Civic required around six years, the Mercury Mariner and Toyota Camry around eight years, and the now discontinued Honda Accord over eleven years. Toyota's other hybrids (Highlander, Lexus RX 400h and Lexus GS 450h) had paybacks ranging from 13.6 to 15.5 years and these will now be significantly longer with the loss of federal incentives.

In August 2007, with figures that do not reconcile with those from 2006 given that Toyota's federal incentives had reduced and gasoline was US$2.77 per gallon, Edmunds.com published data that suggested a payback period of 6.5 years for the Highlander, 10.2 years for the RX 400h and 6.9 years for the GS 450h.

Competition from diesels

A significant barrier to the adoption of hybrids in Europe and some Asian countries, particularly South Korea and India, has been the popularity of diesel-powered light passenger vehicles, which can return 25% - 30% better fuel economy than equivalent gasoline-powered vehicles. Furthermore, the purchase price premium for a diesel over a gasoline vehicle is somewhat less than the premium associated with a hybrid and the payback period proportionally shorter.

With global light vehicle production forecast to reach around 87 million by 2015, the diesel share of this is expected to increase from 16 million (23.6%) in 2007 to around 26.4 million (29.9%) by 2015. More than 50% of new light passenger vehicle sales in Europe are diesel-powered, as are around 40% in South Korea and 35% in India, and these figures are forecast to increase to 57%, 56% and 50% respectively by 2012. Consequently, it seems unlikely that hybrid sales will grow substantially in those countries unless national and local governments provide incentives and/or OEMs can markedly reduce hybrid drivetrain production costs.

To date, diesels have been unpopular in North America to the degree that new diesel passenger car sales have been banned in four US states for some years. However, that is now changing with the introduction of low-sulphur diesel and exhaust after-treatment technology that enables diesels to already meet future emissions standards such as Euro 6 and US BIN 5. Diesels have also become quieter and more driveable during the last decade with performance equalling, and some cases exceeding, that of gasoline-powered cars. Diesel light vehicles in North America accounted for a 3% market share in 2007 but that is forecast to rise to around 12% by 2015.

Two European diesels that are similar in size and performance to a Toyota Prius, the Citroen C4 1.6 HDi and the Renault Megane 1.5 dCi, provide a comparison of diesel and hybrid fuel economy. The Prius outperforms the other

two in city driving, but they both outperform it on the highway with the result that they do not fall far short on the European combined test cycle. In terms of CO2 emissions, however, diesel is more carbon intensive and the Prius wins that competition.

Table 1: European test cycle fuel economy estimates (mpg)

Vehicle	City	Highway	Combined	C02 (g/km)
Citroen C4 1.6 Hdi 16v	48.7	74.3	62.8	120
Renault Megane1.5 dCi	50.4	70.6	61.4	120
Toyota Prius	56.5	67.3	65.7	104

Source: uk.cars.yahoo.com

In terms of payback, the 2007 Edmunds.com data provides a comparison of diesels versus hybrids in the US. The study included three diesels and three hybrids, with a sedan and two SUVs in each category. In all cases, the gains in fuel economy over the gasoline-only equivalents were similar but the diesels posted much shorter payback periods because of lower purchase price premiums.

Table 2: Payback periods for diesels versus hybrids in the US

Vehicle	Combined mpg	Gain over gasoline (%)	Payback (yrs)
Mercedes-Benz E-Class diesel	32.0	35.2	1.7
Mercedes-Benz M-Class diesel	25.0	27.1	2.1
Jeep Grand Cherokee diesel	23.3	27.3	3.8
Toyota Highlander hybrid	29.7	39.4	6.5
Lexus GS 450h hybrid	27.0	19.3	6.9
Lexus RX 400h hybrid	29.7	27.5	10.2

Source: edmunds.com (Errors found in the original data have been corrected)

Chapter 3: Types of Electric Hybrid Drive System

TYPES OF ELECTRIC HYBRID DRIVE SYSTEM

As has been mentioned, hybrid drive systems that use an ICE and one or more electric motors can be configured in several different ways: 'series', 'parallel', or a combination of both such as the currently-popular 'input-split' and 'combined-split' systems. Hybrids are also classified as 'full', 'assist' or 'mild', depending on the degree to which the electric drive can propel the vehicle. All hybrid systems feature 'regenerative braking' - the capacity to recover kinetic energy and store it electrically by exploiting an electric motor's capacity to function as a generator when externally driven by the vehicle's momentum.

Series

A series hybrid has no mechanical connection between the ICE and electric motor(s) and is essentially an electric vehicle that carries an on-board electricity generation system powered by an ICE that can be operated in its most efficient range. If the system includes a battery, either or both the ICE-generator combination and the battery can be used to drive the electric motor(s). If the system does not employ a battery, the ICE must operate at all times to drive the generator and power the motor(s).

There is currently only one series hybrid light vehicle in the market, the Renault Kangoo car-based van. GM's Opel Flextreme and Chevrolet Volt concepts use a series configuration because they are primarily intended as 'plug-in' electric vehicles that are recharged from an external electricity source but which also carry an onboard recharging system to provide extended range. The Volt is scheduled for production in 2010.

Parallel

Parallel hybrid systems employ a mechanical transmission that connects both the ICE and the electric motor(s) to the driving wheels although both systems do not always power the vehicle. Typically, parallel hybrids switch off the ICE when the vehicle is slowing or stationary and use the electric motor to launch it again, or at least to assist the ICE during the launch process. Considerable electrical storage capacity is required for electric-only or assist propulsion, as well as to operate electrically-powered ancillary systems such as power steering, brake boosters and air conditioning when the ICE is switched off.

Series/Parallel

A series/parallel hybrid system combines the advantages of both systems but, as in the series configuration, involves the use of a separate generator so that the ICE can generate electricity when the electric motor is being used to provide motive power.

Input-split

The Toyota Hybrid System (THS) is an example of a series/parallel, input-split hybrid in which the drive from the ICE and the electric motor is split via a planetary gear set so that either or both can drive the road wheels. This enables the use of a smaller ICE and provides a relatively simple form of continuously-variable transmission (CVT) although the transmission efficiency varies considerably depending on the amount of power being delivered by the electric motor.

Combined-split

Several OEMs and suppliers have been developing so-called 'two mode' hybrid systems that use two electric motors to provide two speed ranges under electric power. These are typically combined-split systems that require two planetary gear sets and two clutches but enable the use of smaller electric motors with combined weight and packaging requirements that can be less than those of the single electric motor required for a wider speed range. The first two-mode system to market was developed jointly by GM, BMW and DaimlerChrysler and was launched on the 2008 Chevrolet Tahoe Hybrid.

Full hybrid

A full hybrid is distinguished by its capacity to operate for extended periods on electric power alone. A high-capacity electrical storage system is required and motive power can be provided by either the ICE or the electric motor(s), or a combination of the two. The electric motor(s) enable regenerative braking.

With its regenerative braking and stop-start functions, a mild hybrid can provide a fuel economy gain of around 10%

When the vehicle is slowing or stationary, the ICE is switched off until the driver presses the accelerator. The vehicle is launched from rest by the electric motor and the ICE restarted again when required for extra power or to recharge the battery. This takes advantage of the different torque characteristics offered by ICEs and electric motors: an ICE produces low levels of torque at low engine speeds whereas an electric motor produces maximum torque from rest and maintains it throughout a wide speed range.

The electric-only launch capability also avoids the use of the ICE during its least efficient and most polluting operating range, and enables the use of a smaller ICE since engine torque requirements are generally dictated by the required acceleration capacity. In a conventional vehicle, this results in an ICE that is larger than required to maintain a steady cruising speed.

Assist hybrid

An assist hybrid does not have the capacity to operate solely on electric power but simply uses the electric motor to provide assistance to the ICE, particularly during acceleration. Consequently, an assist system tends to use a lower-power electric motor and a significantly smaller battery than a full hybrid, and enables the use of a smaller ICE.

Honda's hybrids have so far been assist hybrids that use the company's Integrated Motor Assist (IMA) system that consists of an integrated starter-alternator damper (ISAD) (see 'Enabling Technology'). The ISAD also enables the regenerative braking and ICE 'stop-start' functions.

Mild hybrid

The distinction between assist and mild hybrids is not altogether precise and the terms tend to be used somewhat interchangeably. In this report, 'mild' hybrid is used to refer to those that provide limited electric drive assistance via an ISAD or belt-driven alternator-starter (BAS), generally only during the first phase of launch from rest. Nevertheless, with its regenerative braking and stop-start functions, a mild hybrid can provide a fuel economy gain of around 10%. The first mild hybrid to market was the 2004 Chevrolet Silverado/GMC Sierra hybrid that used a 14kW ISAD. The first-generation GM Saturn Vue Green Line achieved similar functioning by using a BAS.

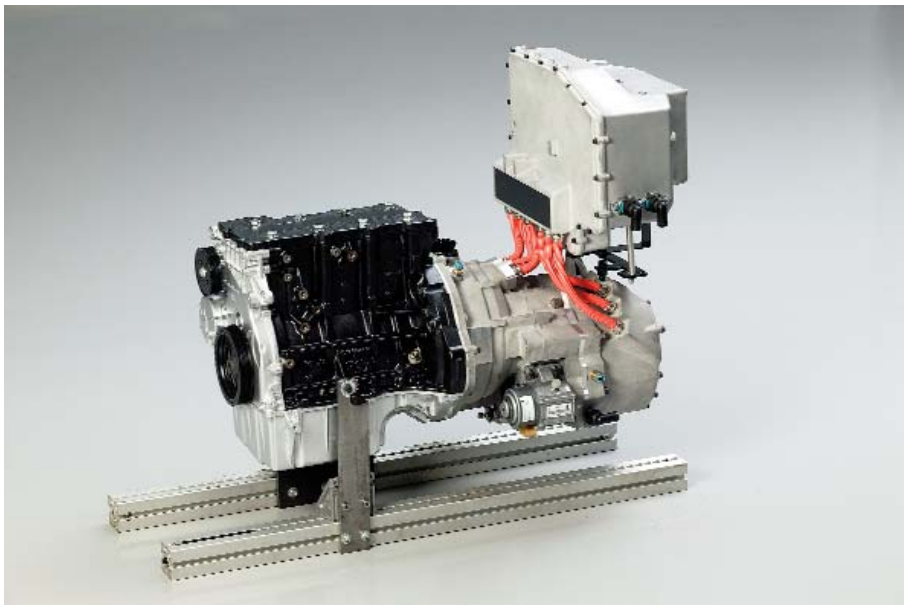
Diesel hybrids

Because diesel ICEs offer superior fuel economy over their gasoline counterparts, their use with a hybrid drivetrain has considerable appeal. The hybrids produced under the US PNGV were diesels and Audi's short-lived Duo was a turbo-diesel hybrid. However, diesel engines cost more to produce than gasoline engines, adding an additional price premium to that associated with hybrid technology.

During the last few years, some supplier collaborations have produced diesel hybrid concept vehicles. In 2002, Ricardo and Valeo, developed the ISAD-based "I-MoGen" (Intelligent Motor Generator) mild hybrid drivetrain that returned up to 25% better fuel economy than a conventional diesel and was 30% lighter despite the addition of hybrid components. In 2005, Ricardo, PSA Peugeot Citroen and the UK-based aerospace company, QuintiQ, developed a full hybrid diesel version of the Citroen Berlingo car-based small van. It returned around 75mpg, emitted 99gm/km of CO2 and exceeded Euro 4 standards for other emissions.

For the 2006 UK Department of Transport's Ultra Low Carbon Car Challenge, Zytek produced a plug-in hybrid version of a smart forfour diesel that returns 88mpg (3.2litres/100km) and emits only 85gm/km of CO2. The drivetrain is packaged within the space occupied by the normal transmission and uses an ISAD and a separate electric motor connected through a CVT transmission designed by Xtrac.

Figure 2: Zytek diesel hybrid drivetrain



Source: Zytek Group Ltd

DaimlerChrysler produced 100 Dodge Ram hybrid diesel pick-ups in 2004 to field test the technology and several other OEMs have been researching diesel hybrids during the last three years. Some have presented diesel hybrid concepts at motor shows, including:

- An Opel Astra developed by GM and DaimlerChrysler that returned around 59mpg.
- Ford's Mercury Meta One crossover and Reflex sports car.
- A Volkswagen model for which the company claimed 118mpg (US gallons).

In 2006, PSA Peugeot Citroen showed two diesel hybrid demonstrators, the Peugeot 307 and Citroen C4 Hybride HDi, but later announced that it had delayed production until around 2010. Toyota and Isuzu have also announced that they aim to produce a diesel hybrid by 2010 and Bosch is working with an unnamed OEM on a diesel hybrid. The Chinese OEM, Chery, plans to launch a hybrid that is understood to be a diesel during 2008.

Chapter 4:
Enabling technology

ENABLING TECHNOLOGY

The development of hybrid vehicles has driven the advancement of several major automotive technology areas, including batteries, electric motors, starter-alternator systems, electrically-powered ancillaries, electronic control systems and high-voltage electrical architecture.

Batteries

Battery technology is central to the success of a hybrid drivetrain and the growing interest in electric cars and plug-in hybrids with large batteries has attracted enormous R&D investment in the sector. Currently, the cost of the battery pack contributes around one third of the cost of adding a hybrid drivetrain and a considerable proportion of the added weight.

Weight, the resultant low energy density (30 – 50Wh/kg), high operating costs due to a short service life and environmental concerns mean that the traditional lead-acid automotive battery has not been a contender for hybrid applications. However, the Advanced Lead-Acid Battery Consortium recently tested a Honda Insight fitted with lead-acid batteries over 100,000 miles and claimed that the technology was competitive with current hybrid batteries and considerably less expensive.

Nickel-cadmium (NiCd) batteries have been used in a wide range of consumer applications for many years but are being phased out because of environmental concerns regarding their cadmium content. They provide energy density of 45 – 80Wh/kg but have a tendency to develop large crystals on the cell plates that result in a charge capacity 'memory' if they are repeatedly recharged after low levels of discharge – a typical pattern in hybrid applications.

Nickel metal hydride (NiMH) batteries became commercially viable during the 1980s and progressed to the extent that Toyota opted for them when developing the Prius and plans to remain with the technology for the third-generation model. Toyota has developed a reconditioning programme for its NiMH batteries that involves replacing any defective cells in the 28-cell pack with cells harvested from another battery of similar age and usage history. The company offers a warranty of eight years or 100,000 miles (ten years or 150,000 miles under California regulations) and claims that reconditioning can add up to six years to a battery's life.

Figure 3: Toyota NiMH battery

Source: Toyota Motor Corporation

NiMH batteries are completely recyclable and offer energy density of 60 to 120Wh/kg. They do not suffer as much from the 'memory' effect exhibited by NiCd but have a higher self discharge rate at 30% per month and service life can be shortened by high discharge rates.

Despite Toyota's confidence in NiMH, the battery technology currently favoured for hybrids and electric vehicles is that of lithium-ion (Li-Ion), which currently offers energy density ranging from 90 to 190Wh/kg although some researchers have claimed levels as high as 2,000Wh/kg. Currently, four Li-Ion technologies are attracting extensive R&D attention: Li-Ion Cobalt, Li-Ion Manganese, Li-Ion Phosphate and Li-Ion Polymer.

Li-Ion offers a low-maintenance battery with no charge memory effect and a self discharge rate lower than 10% per month. However, relatively short service life and battery safety remain major foci of research. Protection circuitry has been necessary within each cell to limit peak voltage during charge and low voltage during discharge, adding to the cost of an already expensive technology. Added to this, Li-Ion batteries are vulnerable to overheating and require cooling systems, an issue that is currently the subject of considerable R&D investment.
During recent months, several advances in Li-Ion technology have been announced:

- Advanced Battery Technologies has successfully developed a polymer Li-Ion battery cell using lithium iron phosphate that provides advantages over previous technologies, including greater resistance to overcharge, increased safety and a longer life cycle.
- ExxonMobil Chemical and its Japanese subsidiary, Tonen Chemical, have developed new film technologies that enhance the power, energy efficiency, safety, reliability and affordability of large capacity Li-Ion batteries.
- Toshiba has developed the SCiB (Super Charge ion Battery), a fast-charging battery that the company claims provides excellent safety, a life cycle of more than ten years and high current recharging that enables a 90% recharge in just five minutes.
- A German consortium that includes BASF, Bosch, Evonik Industries, Li-Tec, Volkswagen and Germany's Federal Ministry for Education and Research is focusing on the use of a new system of separators within Li-Ion batteries in order to overcome the limitations imposed by the current plastic separators that lose their stability at temperatures above 140 degrees Celsius. The patented separators consist of flexible, nano-material ceramic that is significantly more temperature-resistant and can provide safer, more reliable and longer-lasting Li-Ion batteries.

Alongside the intensive R&D efforts being undertaken by several suppliers, Li-Ion batteries are already being tested in experimental hybrid applications and are at the threshold of series production with high-end application orders already being received, such as for the 2009 Mercedes-Benz S 400 hybrid. Mass production scales are expected to progressively reduce costs.

The Chinese automotive manufacturer, BYD, has announced that it will launch a hybrid vehicle during 2008 that uses a super-iron battery. Super-iron batteries are considered by many to still be in the early stages of development, particularly in the larger applications required to power hybrid vehicles. The technology was first announced by researchers at the University of Massachusetts in 1999.

If super-iron batteries can be successfully brought into mass-market applications, they offer the promise of holding three times the charge capacity of nickel-based batteries, they provide stable voltage levels even under high discharge rates and they can be recharged to 70% capacity in ten minutes. Furthermore, using iron salts for the cathode material would significantly reduce costs and virtually eliminate the recycling and safety concerns associated with other battery technologies.

An alternative electrical storage technology to batteries is that of the super- or ultra-capacitor, which has already been applied to a hybrid drivetrain on the Nissan Diesel Capacitor delivery truck. Super-capacitors (supercaps) have extremely rapid charge and discharge rates making them ideal for accumulating charge from regenerative braking systems and for providing electrically-powered acceleration. They also have the advantages of lasting indefinitely and of requiring no maintenance.

However, the energy density of supercaps is not high and they lose voltage as they discharge, limiting their application as the sole energy storage system to mild hybrids or as a high-discharge facility in conjunction with a battery to enable the use of a smaller battery pack. Mercedes-Benz intends to use supercaps for the regenerative braking and torque assist elements in its hybrid drivetrains.

As an adjunct to the battery in an electric vehicle, supercaps have been found to increase acceleration by up to 15% and operating range by more than 20%.

Plug-in hybrids

A plug-in hybrid is a hybrid with a larger battery pack, a facility for recharging the battery from an external electricity source and control software that allows a deeper battery cycle so that the vehicle can operate solely on electricity until the battery charge level is almost exhausted.

A plug-in hybrid could equally be described as an electric car that carries an ICE to extend its range. For example, GM's forthcoming Chevrolet Volt is a series hybrid that is designed to operate primarily on electric energy but which carries its own on-board recharging system in the form of a 1.0-litre, three-cylinder, flex-fuel ICE. The Volt can travel for around 40 miles per charge, which would cover the commute cycle of around 78% of US workers, without using its ICE. GM also claims that, over a 60 mile journey, the Volt returns 150mpg although an estimate of the average cost per external charge was not provided.

Figure 4: Chevrolet Volt

Source: General Motors Corporation

Plug-in hybrids have enormous appeal from the consumer's point of view because electricity is relatively cheap and an electric motor is far more efficient than an ICE, resulting in very low fuel costs. In the US and Canada, plug-in conversion kits that consist of additional batteries and a software upgrade for the Toyota Prius have been available for some time and a large group of organisations have formed the Plug-in Partners Coalition in order to promote the technology and seek incentives from government agencies and electricity suppliers.

In opposition to this movement, environmentalists have cynically described electric and plug-in vehicles as "emissions elsewhere vehicles" because in almost all regions the electricity supply is provided, at least in part, by fossil fuel power. Nevertheless, it has been argued that in the US, for example, where more than 70% of the electricity generation is powered by coal, natural gas and oil, the higher efficiency of the supply generation system and the electric car compared to the poor thermal efficiency of an ICE actually result in the electric vehicle outperforming the ICE-powered equivalent in terms of emissions, including CO2.

In balance, it appears that consumer interest is outweighing environmentalist cynicism. A September 2007 survey in the US found that 27% of vehicle owners said they were likely (13%), very likely (8%) or extremely likely (6%) to

purchase a plug-in hybrid as their next vehicle, although the total dropped to 16% when respondents were informed that the price of the technology would add US$3,200 to the purchase.

A September 2007 survey in the US found that 27% of vehicle owners said they were likely (13%), very likely (8%) or extremely likely (6%) to purchase a plug-in hybrid as their next vehicle

In response to the level of consumer interest, significant momentum is developing amongst OEMs, suppliers and researchers in the quest to bring plug-in technology to market. Research teams in a number of US institutions are testing the technology and researching consumer attitudes. In addition, the US Department of Energy's Office of Energy Efficiency and Renewable Energy has selected five plug-in hybrid battery development projects for US$17.2m in funding that will be combined with over US$20m from the US Advanced Battery Consortium.

Alongside these efforts, some OEMs and suppliers are already launching the technology. In 2004, Mercedes-Benz displayed a plug-in option for its Sprinter Hybrid diesel that has a range of 30km on solely electric power and in 2006 GM announced that it planned to produce a plug-in version of the Saturn Vue hybrid with Li-Ion batteries and an electric-only range of around ten miles (16km).

Volvo displayed its C30-based Recharge plug-in concept car at the 2007 Frankfurt Motor Show. The Recharge is a series hybrid with four wheel motors and an electric range of up to 100km. Volvo claims that the car is expected to emit 66% less CO2 than a normal hybrid and its operating costs are 80% lower than a gasoline-powered car. It can be recharged in three hours, but a one hour charge will give it an electric range of 50km (30 miles).

Toyota has announced that it will launch a plug-in hybrid by 2010 and is working with Electricite de France to jointly develop recharging points in major European cities, where most owners park their vehicles on the street overnight.

Electric motors

The electric motor is the defining feature of a hybrid drivetrain, using the electrical energy stored during regenerative braking and enabling the ICE to be reserved for use in its more efficient operating range. It can also be used to provide additional torque for acceleration, enabling the use of a smaller ICE. Furthermore, by providing maximum torque from standstill, the electric motor symbiotically compliments an ICE, which is inefficient and produces low torque at low rotational speeds.

During its initial, high-torque phase, an electric motor delivers a constant torque output but then shifts into an 'extended' speed range in which its torque output decreases proportionally with its speed, resulting in constant power output. Typically, the extended range is around twice that of the constant-torque phase and once exceeded, power drops off rapidly although high rotational speeds can still be attained. This phenomenon enables the electric motor to be configured to provide a launch phase, steady power during its extended phase and a diminishing amount of drive at higher speeds.

The principal of the direct current (DC) electric motor was first demonstrated by Michael Faraday in 1821 and the first commutator-type motor capable of practical application was developed by William Sturgeon in 1832. Although the DC motor is relatively simple and inexpensive to manufacture and offers easy speed control, the use of sliding contacts via brushes and a commutator that wear against one another creates the need for regular maintenance and component replacement.

The first brushless electric motor was developed by Nikola Tesla in 1883 and its commercial launch in 1888 enabled the long-distance distribution of alternating current (AC) electricity, enabling what some have called "the second industrial revolution". AC motors rotate by creating a rotating magnetic field in the stationary body of the motor that induces the rotor to follow. When loaded, the rotation of an induction motor tends to lag and become asynchronous to the movement of the stator's magnetic field, however, the design can be advanced to create synchronous motors in which the stator magnetic field keeps the rotor synchronised and results in higher efficiency.

Asynchronous induction motors are simple, relatively inexpensive to produce and are rugged and reliable. They are often termed “the workhorses of industry” and range in power from fractions through to thousands of kilowatts. For high power applications, the use of a multiple-phase power supply (usually three-phase) enables the use of a smaller frame size and reduces the individual phase current demands. Asynchronous induction motors have been used in some heavy hybrid bus and truck applications by Allison Transmission and Hino.

Synchronous AC motors have a more complex and expensive rotor design than their asynchronous counterparts and consequently are not as widely used in industry. The main design types are permanent-magnet, field-wound and switched reluctance, of which the permanent-magnet type has proven to be the most suitable for automotive applications. It is less expensive to manufacture than the field-wound type and requires less electrical power because it does not electrically generate the magnetic field. The switched reluctance design is the simplest and least expensive and offers excellent performance characteristics for electric vehicle application. However, it requires electronic control and the torque pulses generated produce vibration and noise.

So far, in light vehicle hybrids, the permanent-magnet, three-phase, synchronous motor has been preferred and development has progressed significantly. Hitachi, through five generations of development, achieved a massive 450% improvement in power-to-weight resulting in size and weight reductions that brought the technology to viability for automotive applications. Toyota achieved a 50% increase in electric motive power with its second-generation THS system launched in 2004, although some of that was achieved through an increase in battery voltage. Honda has concentrated on the development of internal permanent-magnet motors and by its third generation had achieved torque increases of more than 20% along with an efficiency improvement of nearly 3% to an impressive 97.5%.

Regenerative braking

A central feature of hybrids is that of recovering kinetic energy during slowing and braking and storing it electrically for later use as motive power. This feature is achieved through the use of the electric motor’s capacity to operate as a generator when driven by an external rotational force such as the vehicle’s drivetrain.

When the vehicle is coasting or when the driver operates the brake pedal, the electronic control system switches the electric drive motor to generator mode, essentially using it in the way that an ICE can be used for engine braking to supplement the efforts of the braking system. The AC electrical energy produced by the motor/generator is converted to DC by an inverter so that it can be stored in the battery.

Toyota’s THS system incorporates a designated generator as well as the electric drive motor, with the generator driven by the transmission’s planetary power-split device so that it can be powered by the kinetic energy being directed through the transmission by the vehicle’s momentum. To maximise the regenerative braking potential, the driver must use the ‘engine braking’ effect as much as possible and the wheel brakes as little as possible. According to Toyota, optimising the regenerative braking effect in that manner in a Prius can save as much one litre of gasoline per 100km in urban driving.

Electrically-driven ancillaries

Automotive manufacturers have been developing electrically-powered ancillary systems in the quest to improve fuel efficiency and reduce CO2 emissions. Ancillaries such as power steering and air conditioning have traditionally been driven by belts and hydraulic pumps that consume energy even when they are not required in operation. Similarly, engine water and oil pumps that must supply adequate flow volumes at low engine speeds waste - and literally spill - excess energy at higher speeds. These systems are progressively being converted to electric power so that they operate only as and when required.

The development of hybrids, which must operate at times without the ICE running, has stimulated the development of electrically-driven ancillaries and braking systems. Alongside this, there has been considerable discussion regarding the need for vehicle electrical architecture with higher voltage levels than the traditional 12/14-volt system,

which cannot provide the electrical power required without high current demands and heavy wiring systems. For some years, there have been proposals to shift to a 36/42-volt standard, but little progress has been made. However, hybrids, with their high-voltage battery systems, can easily support the proposed voltage standard and provide the power required to operate several electrically-driven ancillaries.

Integrated starter alternator damper

The belt-driven generator or alternator has been an essential component in automotive electrical systems but it, too, is now being replaced by more energy-efficient technology in which the alternator is integrated into the engine torque damper flywheel. This has the added advantage of its capacity to function as the engine starter motor without the complexity and noise of the traditional system and the combination is known as an integrated starter-alternator damper (ISAD).

If the ISAD unit is powerful enough, it can operate as the electric drive motor and regenerative braking generator in a mild hybrid, enabling launch from rest, torque assistance during acceleration and quiet engine starting at higher engine rotational speed. ISADs have already been used as the basis of several mild hybrids, starting with the Honda Insight in 1999. Through enabling stop-start and regenerative braking, an ISAD can deliver significant fuel economy improvements and its torque assistance capacity can be used to smooth the gearshifts in an automatic transmission.

An ISAD is no more expensive to produce than the components it replaces resulting in the cost of the battery and control systems as the only additional component expenses in producing a mild hybrid. An ISAD can also support a 36/42-volt electrical system and the high electric power capacity that is already required in some high-end vehicles that are taxing the traditional belt-driven alternator's capability. Furthermore, legislation that requires ICEs to be switched off when vehicles are stationary is being considered in all main jurisdictions and the ISAD is ideal for providing that function.

Figure 5: Continental ISAD

Source: Continental AG

Belt-driven alternator starter

For lighter vehicles, a belt-driven alternator starter (BAS) can serve a similar function to an ISAD in terms of stop-start, regenerative braking and gearshift smoothing functions but the technology's capacity to provide torque

assistance for launch and acceleration is limited by the torque handling capacity of the belt. As a consequence, claims for fuel economy improvements are generally modest but have ranged from a few percent to as much as 15%.

Ricardo and Land Rover, which will be responsible for improving vehicle fuel efficiency, have made the point that although hybrid vehicles are a step in the right direction, they could be even more fuel efficient if they have a control system that carries data about its surroundings

Although larger than a traditional alternator, a BAS is not significantly more expensive to produce than the components it replaces and can be fitted into existing vehicle platforms and engine compartments without significant modifications. It can also support a 36/42-volt electrical system and charge a battery capable of operating electrically-powered ancillaries when the ICE is switched off. To date, BMW, Daimler, GM and PSA Peugeot Citroen have used BAS technology on their stop-start and mild hybrids.

Stop-start

Stop-start technology in various configurations is an essential element of any hybrid drivetrain so that the ICE can be switched off when not required and seamlessly restarted again when it is needed. The components required are either a BAS or an ISAD and the requisite electronic control units (ECU). Stop-start systems alone, while not constituting a hybrid drivetrain in their own right, can significantly contribute to fuel economy.

The Citroen C3 Stop & Start switches off the 1.4-litre 67kW (90hp) gasoline engine just before the vehicle comes to a standstill and then uses a BAS to almost silently restart within 400 milliseconds of the driver releasing pressure on the brake pedal. Citroen engineers recorded a 15% reduction in fuel consumption but an independent test conducted in the UK claimed a 27% reduction, supporting a research finding that fuel consumption could be reduced as much as 30% in heavily-congested urban traffic. Official government fuel consumption figures are 40.9mpg for the urban test cycle, 57.6mpg for the highway cycle and 49.6mpg for the combined, while CO2 emissions are estimated at 135g/km.

The C3 Stop & Start uses a BAS supplied by Valeo and in early 2006 the company launched the technology on the C2, again claiming around 15% improvement in fuel economy and 50.5mpg for the combined test cycle.

Daimler also used a BAS systems supplied by Valeo on the smart fortwo and in July 2007 announced that the entire Mercedes-Benz range would incorporate similar technology, beginning with the A and B Class ranges that September. The OEM's larger vehicles are expected to use an ISAD. In September 2007, the company launched stop-start on its Mercedes-Benz Sprinter vans. Once the ICE has been idling and the transmission in neutral for more than three seconds, the ICE is switched off and restarted again as soon as the driver depresses the clutch pedal. Fuel savings are claimed to be between 5% and 8%.

BMW has also launched the technology, as from March 2007, on the 1-Series and from September on the Mini. The stop-start system is supplied by Bosch and the OEM claims a fuel economy improvement of up to 8%.

Electronic components

A hybrid vehicle requires a number of electronic components unique to its combination of ICE, electric drive and electrical energy storage. These include voltage converters, AC-DC inverters, intelligent power units (IPU) and extra wiring harnesses that include a high-voltage system. Also, because hybrids require a number of electrically-powered ancillaries, such as electric power steering and air conditioning systems, sensors and ECUs are required to manage their operation.

A DC-DC electric converter is required to convert the high-voltage supply to a lower voltage, typically 14- or 42-volts, to power the electrically-powered ancillaries as well as the vehicle's lighting, wipers and infotainment accessories. An inverter converts DC from the battery into AC to power the electric drive motor and, conversely converts AC from the motor/generator into DC to recharge the battery during regenerative braking. The IPU manages

these processes while continuously monitoring the voltage, current loading and temperature of the high-voltage battery and operating the battery cooling system as required. It will also shut down the high-voltage system if the vehicle is involved in a crash in order to protect passengers and rescue workers who might need to cut into the vehicle.

The ICE, electric motor and transmission are controlled by one or more ECUs that determine, in conjunction with data from the IPU, whether the vehicle is powered by the ICE, the electric motor or both, and which mode or ratio the transmission is operating in.

Intelligent control

In December 2007, Ricardo, Orange Business Services, Land Rover, British Ordnance Survey and the Transport Research Laboratory (TRL) announced that they had formed a partnership aimed at improving the efficiency of road transport and reducing its environmental impact through Intelligent Transport Systems (ITS). Partial funding for the 18-month project will come from InnovITS and the UK ITS Centre of Excellence for Transport Telematics and Sustainable Mobility. The project will focus on developing advanced vehicles that can use technologies such as GPS and telemetry to improve fuel efficiency and emissions.

Ricardo and Land Rover, which will be responsible for improving vehicle fuel efficiency, have made the point that although hybrid vehicles are a step in the right direction, they could be even more fuel efficient if they have a control system that carries data about its surroundings and can adapt the drivetrain's mode of operation when negotiating gradients, junctions, and known areas of congestion.

Orange and Ordnance Survey are responsible for the telematics and mapping aspects of the project and TRL will be responsible for the testing and assessment phase.

Chapter 5: Markets and market forecasts

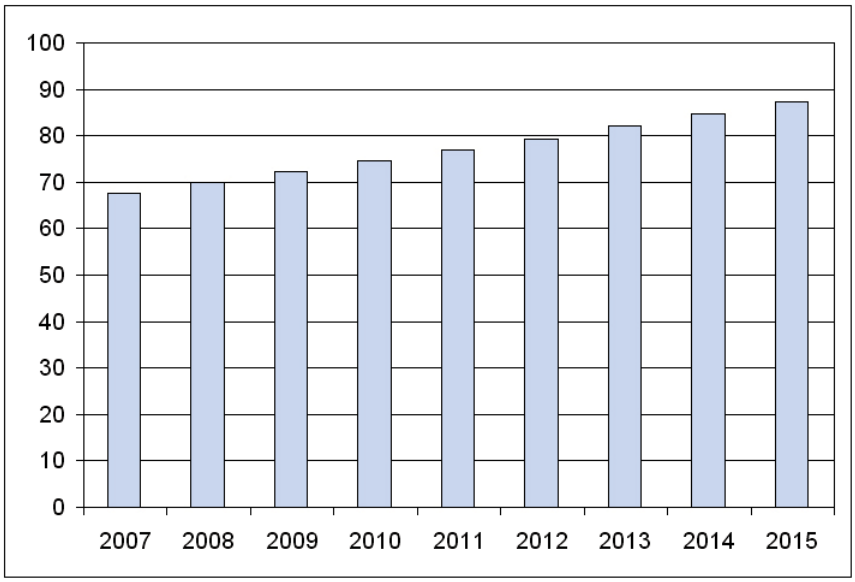
MARKETS AND MARKET FORECASTS

The global light vehicle market

Data from the Organisation Internationale des Constructeurs d'Automobile (OICA) places total global light vehicle sales at around 67.7 million in 2007, assuming similar growth to that of the last few years at around 3.5%. In November 2007, PricewaterhouseCoopers forecast that light vehicle production in 2011 will be 12.7 million higher than the 63.0 million produced in 2005, which represents an average annual growth rate (AAGR) of 3.1% and would take 2015 volume to 85.5 million. In January 2008, J.D. Power & Associates, estimating 2007 production at 66 million, forecast global light vehicle production at 92 million by 2017, which represents an AAGR of 3.4% and would place the 2015 figure at around 87 million.

Taking the 2007 production figure at 67.7 million and assuming growth between the two latter rates above at 3.25% per year, suggests that 2015 production will be 87.4 million.

Figure 6: Global light vehicle production forecast (millions), 2007 - 2015



Some analysts, including Hyundai, have forecast annual light vehicle production growth at around 4% based on high growth projections in the developing regions, particularly in China, India and Asia Pacific where growth could be as high as 8% per year. Rapid growth is also expected in South America, Central & Eastern Europe, and the Middle East, while the mature markets of Western Europe, Japan and North America are expected to grow at rates within the 1 – 3% range.

Against this, forecasts for continuous and possibly dramatic increases in oil and raw materials prices could dampen market growth significantly in all regions, leaving higher projections of global production growth appearing somewhat optimistic. However, increasing oil prices and ever stricter CO2 emissions regulations, while perhaps dampening the global light vehicle market overall, are likely to provide increased growth for hybrid vehicles, both in terms of market share and total sales volume.

The hybrid market to date

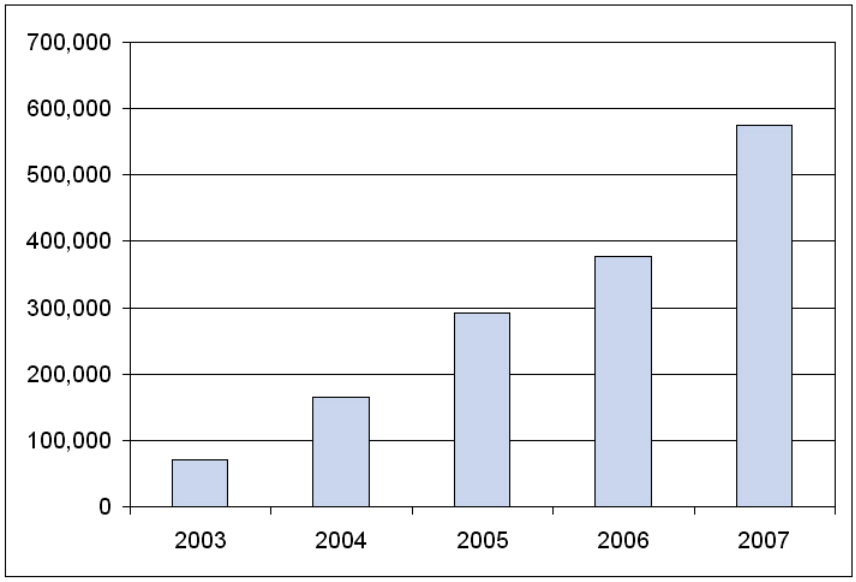
Growth in global hybrid vehicle sales has been dramatic, with annual increases to the order of 135%, 76%, 29% and 53% during the last five years. From sales of around 24,000 in 2000, global hybrid sales stood at an estimated 575,000 during 2007, accounting for around 0.85% of the global light vehicle market.

Table 3: Global hybrid light vehicle sales, 2003 - 2007

2003	2004	2005	2006	2007
70,500	165,900	292,300	377,900	575,00

Sources: Marklines, Paumanck, JD Power, Polk

Figure 7: Global hybrid light vehicle sales, 2003 – 2007



The United States

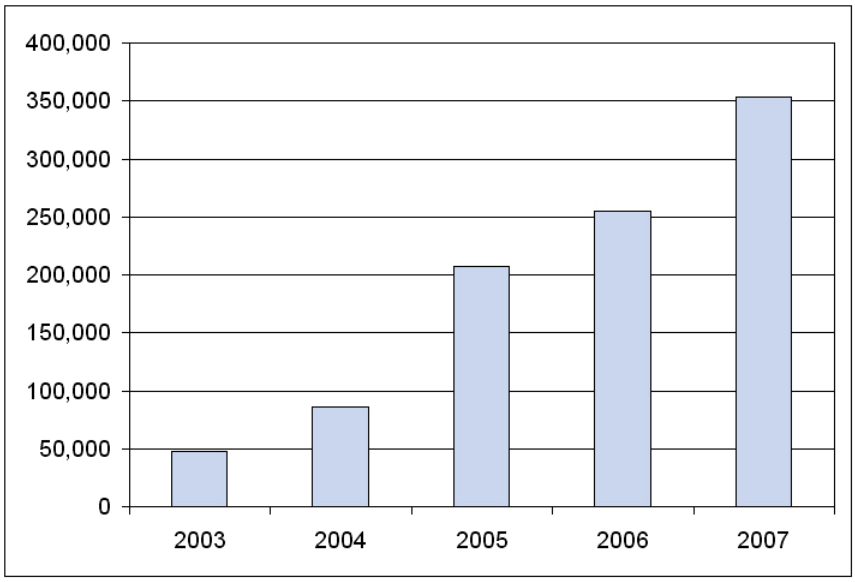
The US has been the main global hybrid market since Honda and Toyota launched their products there in 1999 and 2000 and appears set to remain so in the medium term. In 2007, reported US hybrid sales totalled 347,101 but these do not include GM sales. By the end of the third quarter, total GM hybrid sales to that date were reported at 9,577 and 2007 sales have been estimated at 6,000 to bring the total US sales estimate to around 353,000. Annual increases have clearly been influenced by gasoline prices in the US and have been to the order of 82%, 141%, 23% and 39% during the last five years.

Table 4: US hybrid sales, 2003 - 2007

2003	2004	2005	2006	2007
47,252	86,275	207,734	254,545	353,000

Sources: JD Power, Polk, www.electricdrive.org

Figure 8: US hybrid vehicle sales, 2003 - 2007



Europe

The UK has been the market leader in adopting hybrids in Europe, followed by France, where PSA Peugeot Citroen produces mild hybrids. The penetration of hybrids into the light vehicle market is forecast to be much slower in Europe than it has been in the US, largely because of the popularity, fuel efficiency and lower purchase price of light diesel vehicles, which account for over 50% of new car sales. Some analysts have suggested that hybrid sales will increase in Europe once the price premium for hybrid technology reduces and diesel hybrids become viable in the market.

European drivers, on average, also demand higher levels of drivability and vehicle dynamics than their US or Japanese counterparts, and the image of the hybrid as an electric vehicle makes it unattractive. However, the trend that has seen hybrid technology increasingly being used to enhance acceleration and overtaking performance could work to promote hybrids in the region.

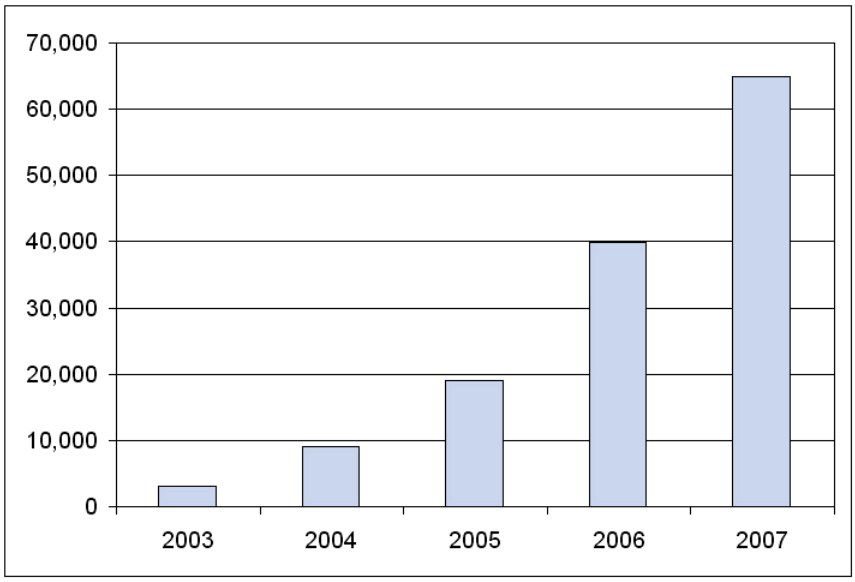
The Toyota Prius and the Honda Civic Hybrid were introduced in Europe in 2002 and sales totalled a mere 1,330. Since then, however, annual increases have been to the order of 126%, 300%, 111%, 110% and 63%. Toyota reported sales of 50,000 hybrids in Europe in 2007 and Honda had earlier forecast 2007 hybrid sales in Europe at 15,000. As a result, hybrid sales in Europe during 2007 have been estimated at 65,000.

Table 5: Hybrid sales in Europe, 2003 - 2007

2003	2004	2005	2006	2007
3,000	9,000	19,000	39,880	65,000

Sources: JD Power, www.hybridcar.com

Figure 9: Hybrid sales in Europe, 2003 – 2007



By July 2007, Toyota's cumulative hybrid sales in Europe had reached 101,235 units, of which over 73,000 were Prius models and the remainder Lexus RX400h and GS450h models. This represents around 10% of Toyota's cumulative global hybrid sales. In comparison, Honda sold around 4,000 hybrids in Europe during 2006 and targeted 15,000 in 2007.

Japan

The Toyota Prius has dominated the domestic hybrid market since its launch in 1997 and Honda has trailed in a distant second place with the Insight and the Civic Hybrid. For the year to 31 March 2007, hybrid sales in Japan totalled 90,410, of which 81,001 were Toyotas and 7,748 were Hondas. Projected 2007 hybrid sales volumes in Japan stand at around 100,000 units, with Toyota accounting for around 89,000 and Honda around 7,900.

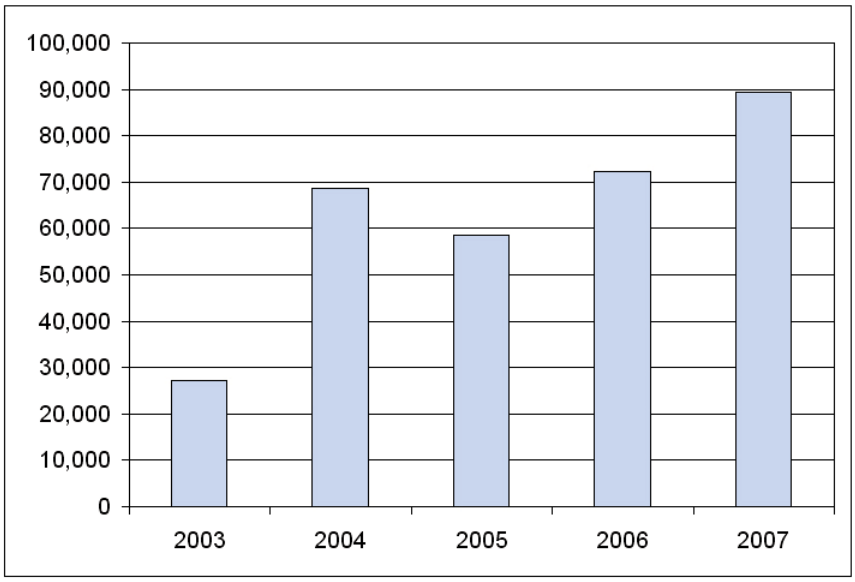
Breakdowns by model, and even total annual sales volumes, of hybrids in Japan are difficult to obtain and must often be extrapolated from Toyota figures for Toyota and Lexus models. As at the end of January 2008, Toyota had published Japan hybrid sales figures up until only May.

Table 6: Toyota hybrid sales in Japan, 2003 - 2007

2003	2004	2005	2006	2007*
27,200	68,700	58,500	72,400	89,300

*Source: Toyota (*estimated from Jan – May figures)*

Figure 10: Toyota hybrid sales in Japan, 2003 – 2007



Source: Toyota

Hybrid market forecasts

Forecasts, being estimates based on available market data and a set of assumptions regarding future developments, always vary from one forecaster to another. To present forecast data in this report, estimates from several sources have been considered. In some cases, several figures have been averaged, in others, one set of data has been selected as the most complete. Where data has been incomplete, or where market data can be compared with forecast projections made earlier, some figures have been interpolated between the data points in hand.

With volatile oil prices, impending regulations to limit CO2 emissions and shifting projections regarding oil reserves and the future supply and demand equation, it is not surprising that forecasts for global hybrid vehicle sales vary considerably. To provide some examples, forecasts during the last two years have included:

By 2010:

- 1.0 million (Global Insight)
- 1.1 million (Advanced Automotive Batteries)
- 1.16 million (JD Power; based on 775,000 for the US)
- 2.0 million (Paumanck Estimates; includes commercial vehicles)

By 2012:

- 1.5 million (Siemens VDO)
- 2.0 million (Continental and ZF)
- 2.2 million (Nomura Research Institute)
- 3.0 million (Strategy Analytics)
- 5.1 million (Paumanck Estimates: includes commercial vehicles)

By 2015:

- 2.0 million (Advanced Automotive Batteries)
- 8.0 million (Paumanck Estimates; includes commercial vehicles)

Apart from the distinctly higher forecast by Paumanck Estimates, which include commercial vehicles, there appears to be a degree of agreement regarding hybrid sales being around 1.1 million units by 2010, but estimates beyond then vary significantly.

With volatile oil prices, impending regulations to limit CO2 emissions and shifting projections regarding oil reserves and the future supply and demand equation, it is not surprising that forecasts for global hybrid vehicle sales vary considerably

In forecasting two million hybrids per year by 2012, Continental and ZF assumed strong hybrid sales growth in China, which could well be the case now that China has announced that incentives will apply that make hybrids more affordable than other cars. The Nomura Research Institute assumed that hybrid costs would reduce, while the model range would increase worldwide.

Discarding the Paumanck figure as somewhat optimistic and averaging the other four suggests a figure of between 2.1 and 2.2 million by 2012. Accumulating the forecast totals arrived at for Europe, Japan and North America (below) results in a figure approaching 2.0 million for 2012. Adding an estimate for sales in the rest of the world also takes the total to somewhere in the vicinity of 2.1 million, which has been selected as the figure to be used in this report. This represents an AAGR of 29.5%, which, if it continued, would take the projected total sales of hybrids in 2015 to around 4.6 million units.

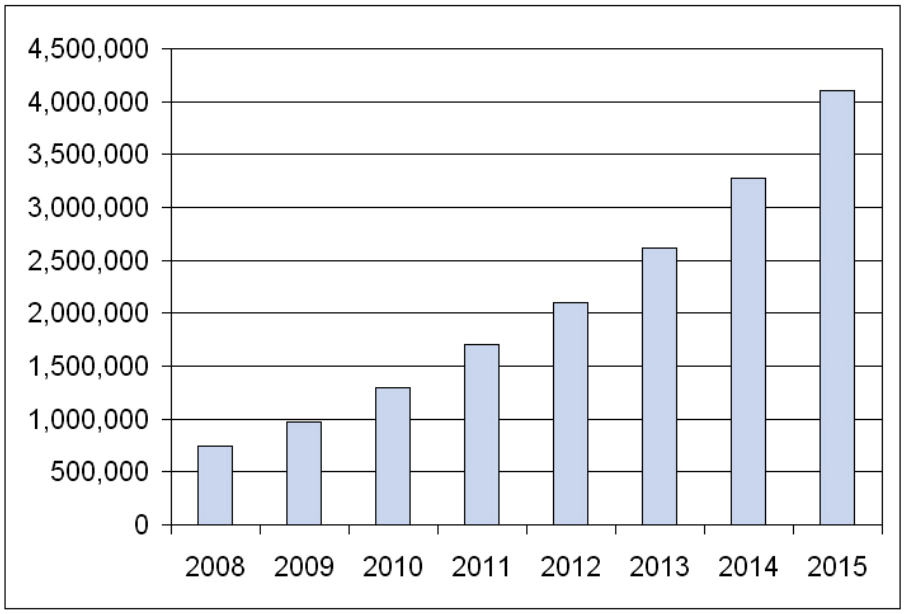
However, several suppliers of hybrid components have forecast an AAGR of 25% during the next few years, although many of these forecasts were made before the rapidly-growing concerns of the last year regarding CO2 emissions and the proposed legislation in the major developed markets that could add considerable impetus to hybrid sales in future. Because of this, the higher AAGR of 29.5% has been used up until 2012 but beyond 2012, the lower AAGR of 25% has been assumed in order to reflect a degree of market saturation of hybrids in the developed markets and the likelihood of dramatic oil price rises beyond the so-called 'peak oil' point, which has been placed by many as likely between 2010 and 2012.

Table 7: Global hybrid sales forecast (millions), 2008 - 2015

2008	2009	2010	2011	2012	2013	2014	2015
750,000	970,000	1,300,000	1,700,000	2,100,000	2,620,000	3,280,000	4,100,000

Sources: Various (see regional forecasts below)

Figure 11: Global hybrid sales forecast, 2008 – 2015



As can be seen in the tables and figures by region below, growth in the developed regions closely follows global growth forecasts, although at a slightly lower growth rate. Growth of hybrid sales in the developing markets, however, has been assumed to occur at a considerably higher rate, reflecting the higher light vehicle growth forecast for those markets.

The United States

By 2012, the number of hybrid models available in the US is forecast to increase to over fifty and will cover more market segments than the current range of choices. Research indicates that consumers tend to purchase vehicles within the same vehicle segment, so a wider range of hybrids could enhance overall sales volumes by providing more consumers with a hybrid choice.

Different market forecasts for hybrid sales in the US have been reasonably consistent during the last two years, although J.D. Power & Associates, for example, have revised their projections upward somewhat from around 623,000 in 2010 and 780,000 by 2012 to almost 775,000 by 2010. Less recently, Siemens VDO forecast around 850,000 for the NAFTA region by 2010 and ABI Research suggested that the total by then could be over one million.

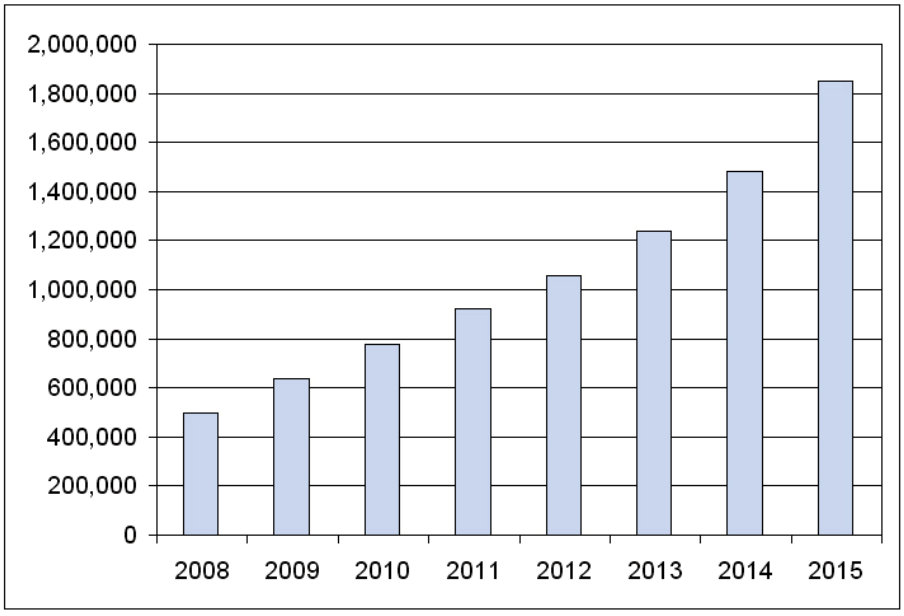
Those figures represent market shares of the around 20.9 million new light vehicles sales forecast for the US in 2010 of between 3.7% and 5.0%. Electric and Hybrid Vehicles Today forecasts 6% by 2013 but GM officials have been quoted as saying that hybrid market share in the US could be as high as 8% by 2012.

Table 8: US hybrid sales forecast, 2008 - 2015

2008	2009	2010	2011	2012	2013	2014	2015
496,000	626,000	775,000	920,000	1,055,000	1,240,000	1,480,000	1,850,000

Source: JD Power & Associates, AutomotiveWorld.com

Figure 12: US hybrid sales forecast, 2008 – 2015



Europe

During recent years, several forecasters and suppliers have estimated hybrid vehicle sales in Europe through to 2015. Frost & Sullivan forecast 450,000 by 2010 followed by rapid growth, taking the total to two million by 2015, whereas Bosch suggested a much more conservative estimate for 2015 at 530,000 hybrid units and Strategy Analytics even more so with a forecast around 400,000 by then.

In 2005, J.D. Power & Associates presented two forecast scenarios – an 'early adopters only' scenario that forecast total hybrid sales in Europe at 760,000 by 2012 and a 'mass market opportunity' scenario that forecast 1.5 million units by then. The 'early adopter' forecast assumed a continuing high price premium and no incentives for hybrids and that some market segments are not covered. The 'mass market opportunity' scenario assumed a lower price premium, incentives and all market segments covered.

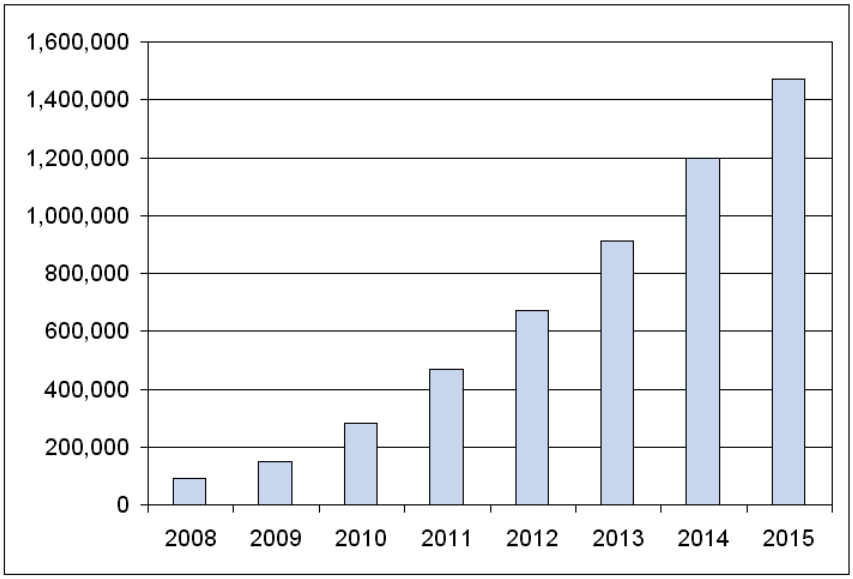
To date, sales figures for 2006 and 2007 have followed the 'early adopter' scenario rather closely so the 2012 forecast for that scenario has been assumed and the interim figures 'smoothed' to arrive at the figures presented in Table 9 below. This does not mean, however, that AutomotiveWorld.com assumes that European hybrid sales will remain the province of early adopters. There will almost certainly be incentives in Europe, at least in the form of licensing tax regimes and congestion charges favouring low emissions vehicles, and there is already a growing spread of models in several market segments. However, because of the oil price concerns mentioned above, growth beyond 2012 has been forecast at a falling rate to 22% by 2015.

Table 9: Hybrid vehicle sales forecasts for Europe, 2008 - 2015

2008	2009	2010	2011	2012	2013	2014	2015
90,000	150,000	280,000	470,000	670,000	910,000	1,200,000	1,470,000

Sources: J.D. Power, AutomotiveWorld.com

Figure 13: Hybrid sales forecast for Europe, 2008 - 2015



Japan

Bosch and other forecasters have estimated that hybrids will achieve a market share of around 5% of the Japanese new light vehicle market between 2012 and 2015, placing hybrid sales volume in the country at around 245,000 in 2012 and 420,000 in 2015.

Table 10: Hybrid sales forecasts for Japan, 2008 - 2015

2008	2009	2010	2011	2012	2013	2014	2015
117,000	140,000	170,000	210,000	245,000	290,000	350,000	420,000

Sources: Bosch, Toyota, AutomotiveWorld.com

Figure 14: Hybrid sales forecasts for Japan, 2008 – 2015

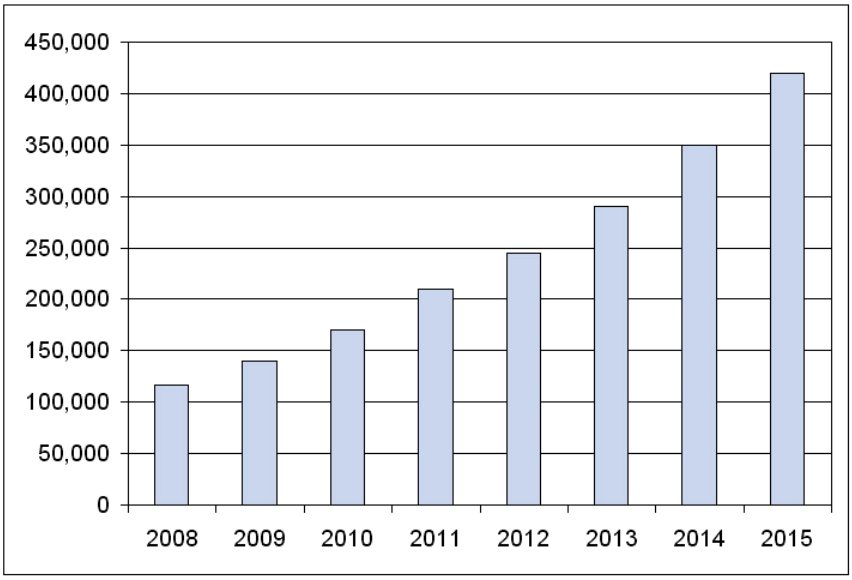
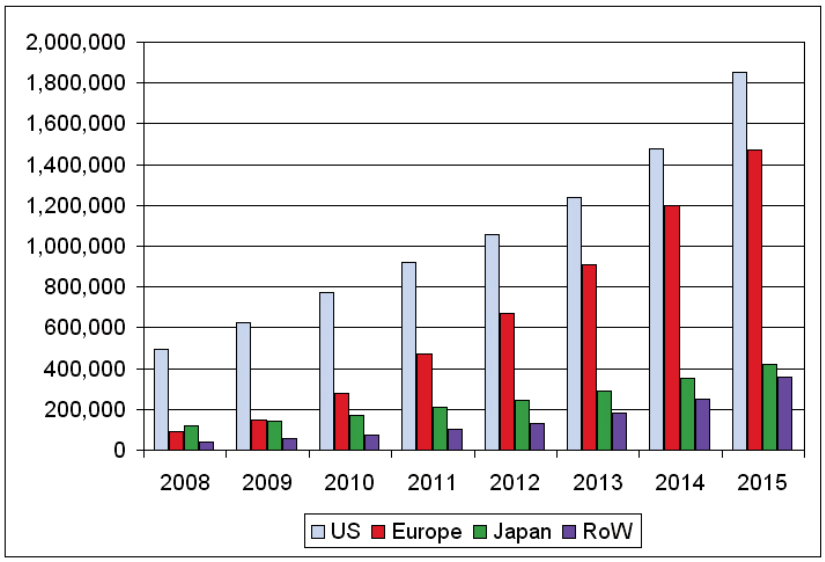


Figure 15 provides comparisons of global hybrid light vehicle sales forecasts by region.

Figure 15: Global hybrid sales by region, 2008 – 2015



China

Hybrid sales in China to the end of 2007 amounted to less than 2,600 Toyota Prius cars during the two years that they had been available. However, in December 2007, the Chinese government announced that hybrids are to receive incentives, from production to ownership, so that they will be cheaper to purchase and operate than non-hybrids. With several Chinese OEMs ready to launch hybrids, this could have a profound effect with the potential to perhaps double global hybrid sales provided Chinese production capacity can be sufficiently increased.

Published figures for passenger car sales in China during 2007 range from around 5.9 to 6.8 million and within this, 48.3% were medium-sized sedans, 17.9% were MPVs and 5.5% SUVs. Although the available hybrid range in China during 2008 will include only compacts and one mid-size sedan, the popularity of MPVs will surely make the production of hybrid MPVs attractive so that at least two thirds of the Chinese new car market could soon receive incentives to include hybrid technology.

The lower sales figure of 5.9 million new cars in China during 2007 translates to a sales volume of 3.9 million medium-size sedans and MPVs. Market forecasts for vehicle sales in China vary widely, with the more conservative forecasters, including the Chinese government, suggesting no more than 10% per year in the longer term. Global Insight has forecast growth of 12.6% for 2008 but their figures for 2012 and 2017 suggest an ongoing AAGR of around 8.5% for that extended period. At that rate, the mid-size sedan and MPV segments would total 7.5 million by 2015. If one quarter of these were hybrids, Chinese hybrid sales would equal the total forecast for the US by that date. If half were hybrids, the Chinese total would equal the combined total for the US, Europe and Japan.

Because electric and fuel cell vehicles will also significantly increase the demand for batteries, analysts have forecast that the global market for Li-Ion battery materials will grow from its current €1.4bn (US$2.06) to as much as €3.9bn (US$5.74bn) by 2015

Hybrid components forecasts

Hybrid vehicles require a range of specialised components, including batteries and supercaps, electric motors and generators, ECUs, IPUs, voltage inverters, compressors and high-voltage wiring. The global market for these components will, of course, increase with hybrid vehicle production growth although the unit prices of most components will tend to fall with production volume increases. Market value is therefore forecast at slightly lower rates of growth than those forecast for hybrid market volume, namely AAGR of 25% from 2008 to 2012 and 20% from 2013 to 2015.

Table 11: Global light hybrid vehicle components markets (US$m), 2007 - 2015

	2007	2010	2012	2015
Batteries, ultrcaps, ECUs	1,249	2,439	3,811	6,586
Motors, generators, IPUs	582	1,136	1,775	3,068
Inverters, compressors, high-voltage wiring	296	578	903	1,560
Total	2,127	4,153	6,488	11,214

Source: Business Communications, AutomotiveWorld.com

Because electric and fuel cell vehicles will also significantly increase the demand for batteries, analysts have forecast that the global market for Li-Ion battery materials will grow from its current €1.4bn (US$2.06) to as much as €3.9bn (US$5.74bn) by 2015.

Chapter 6: Hybrid models

HYBRID MODELS

The current range of hybrids began with the launch of the Toyota Prius in 1997 and Toyota has held a considerable lead ever since in terms of sales volume and the number of model offerings. The company's hybrid drive technology has also been used by other manufacturers, including Ford and Nissan. As at the beginning of 2008, Toyota, including Lexus and Daihatsu vehicles, had launched eleven hybrid models into production, had successfully campaigned a hybrid racing coupe and had recently presented an ultra-light, mini-segment hybrid concept.

The second major player in the hybrid market in terms of model offerings is General Motors. The company had eight hybrid models available at the beginning of 2008, although these were essentially six models in various nameplate variants based on four platforms. The Chevrolet Silverado/GMC Sierra pick-ups have been discounted as true hybrids by many because they feature little more than a stop-start capability through the use of an ISAD, but during 2008 the new models will be full, dual-mode hybrids, as will the 2008 Saturn Vue Green Line and the Cadillac Escalade variant of the Chevrolet Tahoe/GMC Yukon full-size hybrid SUVs launched in 2007.

GM is clearly pursuing the strategy it announced some time back and is progressing steadily from stop-start through mild to full hybrids that use the dual-mode technology first developed for commercial vehicle applications by the company's former subsidiary Allison Transmission and subsequently developed for light vehicles in collaboration with BMW and DaimlerChrysler. Interestingly, the other partners in the enterprise have been considerably slower in putting the technology into production vehicles. BMW is yet to announce plans for the launch of a production hybrid model. Chrysler will launch it in the 2008 Aspen and Durango SUVs. Daimler plans to use it in the 2009 Mercedes-Benz ML 450 SUV and the S300 mid-size sedan at some time yet to be announced. Daimler's smart fortwo will be a mild hybrid that essentially features a BAS stop-start system.

Although Honda was the second OEM to launch a hybrid in the market and stole a march on Toyota by launching the Insight into the US market in 1999, the company has remained considerably behind its Japanese competitor in terms of both hybrid sales volume and model range. The Civic Hybrid continues to be a success, although to nothing like the degree that the Toyota Prius has been. But the Accord V6 Hybrid, despite its combination of hybrid and cylinder deactivation technology, proved to be a market failure alongside its four-cylinder non-hybrid counterpart and production was discontinued at the end of the 2007 model year. The company has announced that a new compact segment model is being developed and the CR-Z hybrid sports coupe is scheduled to launch in 2009.

Ford was the third to market in the US with its Ford Escape/Mercury Mariner/Mazda Tribute offerings, although these used Toyota technology supplied by Aisin, a Toyota subsidiary that restricted the supply to 24,000 units per year. Not surprisingly, Ford has developed its own technology for the 2008 Fusion hybrid.

Other than the Nissan Altima, which also uses Toyota technology, and a few Japanese market offerings with small sales volumes, no other major OEM has brought hybrids to market although most are developing them or currently preparing them for production. Nissan has decided to not use Toyota technology in future and is developing its own hybrid systems, reportedly in collaboration with Bosch. Volkswagen is preparing to launch hybrid variants of the Jetta and Touran and has declared that all future models will have a hybrid version. PSA Peugeot Citroen has presented concepts of three compact diesel hybrids but has stated that it is waiting for the double price premium of diesel and hybrid technologies to become commercially viable, which the company currently forecasts at around 2010.

Although hybrid sales in China have so far been minimal, several plans for local hybrid production were announced during the final few months of 2007. In December 2007, Changan Automobile presented the first locally-developed hybrid, the Changan Jiexun, which will enter series production around August 2008. No less than four other Chinese manufacturers have plans to launch hybrid production during 2008, led by Shanghai GM with the Buick LaCrosse Eco-Hybrid hybrid in January. The other three include BYD, Chery and Dongfeng Honda. Chery's hybrid is understood to be a diesel.

Figure 16: Changan Jiexun hybrid

Source: Chang'an Automotive Group

BYD's hybrid will be a plug-in model and the company has announced that it is targeting sales in both the US and Europe. The company plans to use super-iron battery technology and claims that its vehicle will have a range of 430km on one tank of fuel, with an electric-only range of 100km and a maximum speed of 160kph (99mph).

Dongfeng has announced that it will launch a hybrid in 2010 and Guangzhou Automobile (GAC) presented a hybrid in November 2007 but gave no date for series production. GAC has joint ventures with both Honda and Toyota, but plans to launch own-brand models by 2010. Chery has announced that by 2010, more than half of its vehicles will be hybrids and half of those will use alternative fuel sources such as ethanol to power the ICE.

Table 12 lists past and current hybrid models, and forthcoming hybrids that, as of January 2008, have been announced through to 2010.

Table 12: Past, present and planned light vehicle hybrid production models, 1997 - 2010

OEM	Brand	Model	Segment	Type	Launch
BMW	BMW	X6	Crossover	Full, dual-mode	2009
BYD	BYD	F6DM	Sedan	Full, dual-mode	2008
Changan	Changan	Not known	Sedan	Not known	2008
Chery	Chery	Not known	Sedan	Not known	2008
Chrysler	Chrysler	Aspen	SUV	Full, dual-mode	2008
	Dodge	Ram	Pick-up	Mild	2004
		Ram	Pick-up	Full, dual-mode	2010
		Durango	SUV	Full, dual-mode	2008
Daimler	Mercedes-Benz	ML 450	SUV	Full, dual-mode	2009
		S 400	Full-size	Full, dual-mode	2009
		S 300 Bluetec	Full-size	Full, dual-mode	2010
		E 300 Bluetec	Mid-size	Full, dual-mode	2010
	Smart	ForTwo	Mini	Mild	2007
Dongfeng	Dongfeng	EQ7200HEV	Sedan	Not known	2010
Dongfeng Honda	Dongfeng Honda	Not known	Sedan	Not known	2008
Fisker	Fisker	Karma	Sports sedan	Series plug-in	2009
Ford	Ford	Escape	SUV	Full	2004
		Fusion	Mid-size	Full	2008
	Mercury	Mariner	SUV	Full	2004
		Milan	mid-size	Full	2008

OEM	Brand	Model	Segment	Type	Launch
General Motors	Cadillac	Escalade	SUV	Full, dual-mode	2008
	Chevrolet	Silverado	Pick-up	Stop-start	2004
		Silverado	Pick-up	Full, dual-mode	2008
		Malibu	Mid-size	Mild	2007
		Equinox	SUV	Full	2007
		Tahoe	SUV	Full, dual-mode	2007
		Volt	Coupe	Series plug-in	2010
	GMC	Sierra	Pick-up	Stop-start	2004
		Sierra	Pick-up	Full, dual-mode	2008
		Yukon	SUV	Full, dual-mode	2007
	Saturn	Vue Green Line	SUV	Mild	2006
		Vue Green Line	SUV	Full	2007
		Vue Green Line	SUV	Full, dual-mode	2008
		Aura	Mid-size	Mild	2007
Honda	Honda	Insight	Coupe	Mild	1999
		Civic	Compact	Mild	2002
		Accord	Mid-size	Mild	2005
		CR-Z	Coupe	Not known	2009
		“affordable”	Compact	Not known	2009
Hyundai	Hyundai	Accent	Compact	Not known	2009
	Kia	Rio	Compact	Not known	2009
Mazda	Mazda	Premacy	MPV	Full	2006
		Tribute	SUV	Full	2004
PSA	Citroen	C4 diesel	Hatch	Full	2010
	Pegueot	307 diesel	Hatch	Full	2010
		308 HybrideHDi	Full	2010	
Porsche	Porsche	Cayenne	SUV	Full	2009
		Panamera	Sports coupe	Full	2010
Renault-Nissan	Nissan	Almera Tino	Crossover	Full	2000
		Altima	Mid-size	Full	2006
	Renault	Kango	Small van	Series	2003
SAIC	SAIC	Not known	Sedan	Not known	2008
Shanghai GM	Buick	LaCrosse	Mid-zise	Mild	2008
Subaru	Subaru	Not known	Hatch	Full	2008
Suzuki	Suzuki	Twin	Mini	Mild	2003
Toyota	Daihatsu	Hi-Jet Cargo	Minivan	Mild	2003
	Lexus	RX 400h	SUV	Full	2005
		GS 450h	Mid-size	Full	2006
		LS 600h	Full-size	Full	2007
	Toyota	Prius	Compact	Full	1997
		Crown	Mid-size	Mild	2001
		Estima	MPV	Full	2001
		Alphard	MPV	Full, AWD	2003
		Camry	Mid-size	Full	2006
		Highlander	SUV	Full	2006
		Sienna	MPV	Full	2007
		Supra HV-R	Coupe	Full	2007
Volkswagen	Audi	Q7 3.6 FSI	SUV	Full	2008
	Volkswagen	Jetta	Compact	Full	2008
		Touran	SUV	Full	2008

Chapter 7: Supplier systems and collaborations

SUPPLIER SYSTEMS AND COLLABORATIONS

The increasing popularity of hybrid drive technology has created new opportunities for suppliers, not only for the provision of specialised components such as batteries, electronic control systems, transmissions and electric motors, but also for complete drive system packages. Although some individual suppliers, including Siemens VDO, which produced a Mercedes-Benz C-Class demonstrator during 2007, and Zytek, which produced a smart forfour diesel hybrid in 2006, have presented complete hybrid powertrains, most other such projects are being carried out by supplier collaborations in which the combined competencies of the partners serve to accelerate development.

The increasing popularity of hybrid drive technology has created new opportunities for suppliers, not only for the provision of specialised components such as batteries, electronic control systems, transmissions and electric motors, but also for complete drive system packages

Bosch and Getrag

During 2006, Bosch and Getrag formed a cooperative agreement to develop and market hybrid drive systems. The two companies focused on complete parallel hybrid systems that use dual-clutch transmissions and include complete electronic management components. In this regard, the competencies of the two companies are complementary, with Getrag's extensive knowledge of drivetrain technology and Bosch's of electric motors, electronic engine and transmission management, and power electronics. Bosch also contributes its experience in developing hybrid drivetrain components, including stop-start technology and the electrical and electronic components required for both mild and full hybrids.

Continental and ZF

Continental and ZF also bring complementary and extensive expertise to their partnership, in which each company separately develops the components that require its particular competencies. Continental launched itself into the OEM hybrid market during 2004 by supplying the ISAD and power electronics for the Chevrolet Silverado/GMC Sierra mild hybrid pick-ups. ZF began by developing CVT transmissions for hybrid applications. Together, the two companies are working to extend their hybrid expertise to full hybrids with a range of components that extend to electrically-powered steering and air conditioning systems and electro-hydraulic brake systems.

FEV and Raser

FEV, a US developer of advanced powertrain and vehicle technologies, has entered into an agreement with Raser Technologies to integrate Raser's Symetron electric motor and power electronics technology with a gasoline ICE. During 2007, Raser announced that it had signed an agreement with an undisclosed OEM to produce a plug-in hybrid demonstration vehicle.

Integral Powertrain and NexxtDrive

During 2006, Integral Powertrain and NexxtDrive developed the Supergen i-Hybrid system that combines a hybrid powertain with electrically-powered forced induction to improve fuel economy with both technologies. The Supergen system is designed for use with 12-volt electrical architecture and includes a BAS and a supercap to provide launch assistance. The system is scalable from 1.2-litre to 4.5-litre gasoline engines and can operate as an "interbooster" for a diesel. The compressor uses a continuously-variable Rotrex traction drive that combines input power from an electric drive and the ICE and provides boost pressure up to one bar. The companies expect the system to be in volume production by 2010.

Quantum and UQM

During 2007, Quantum Fuel Systems Technologies won a contract from the US Army to develop a diesel hybrid version of the Aggressor high-performance, light-duty, off-road, 'alternative mobility vehicle'. UQM Technologies, a developer of high-efficiency electric motors, generators and controllers, is supplying Quantum with the propulsion motors and electronic controls that Quantum will integrate into the hybrid system. Prototypes will be tested and evaluated by the Army, which will provide input regarding the eventual vehicle configuration.

Ricardo and Valeo

Ricardo and Valeo collaborated to develop a mild diesel hybrid concept that they called the I-MoGen (Intelligent Motor Generator) that used a small, high-speed diesel ICE, and ISAD, a regenerative braking system and 42-volt architecture. The project team targeted the performance characteristics of a 2.0-litre turbo-diesel ICE and reported a 28% improvement in fuel economy over the conventional unit.

SatCon and Electrovaya

Massachusetts-based SatCon Technology, which develops and manufactures electronics and motor/generators for the alternative energy, hybrid vehicle and advanced power technology markets, has a contract from the US Air Force Research Laboratory to develop a complete conversion package for a hybrid for special operations applications. Electrovaya will develop the vehicle's Li-Ion battery system. SatCon will provide the ISAD, the permanent magnet traction motor/generator and the electrical/electronic system including converters, inverter and distribution bus.

Chapter 8: Battery development consortia

BATTERY DEVELOPMENT CONSORTIA

Several battery development consortia have been formed during recent years in efforts to accelerate the progress of the technology, particularly with respect to Li-Ion batteries.

Advanced Battery Consortium

The US Advanced Battery Consortium (USABC) is part of the US Council for Automotive Research and includes the US Department of Energy, Chrysler, Ford and General Motors. The USABC programme aims to produce a cost-competitive Li-Ion battery that is lighter, smaller and of higher power than existing battery technologies, and has provided grants for battery development work to Compact Power, EnerDel and the Johnson Controls Saft joint venture (see below).

Automotive Energy Supply

Automotive Energy Supply is a joint venture between Nissan Motor and NEC Corporation that was formed in late 2006 to manufacture Li-Ion batteries. The venture plans to begin mass production by 2009.

Cobasys

Cobasys Corporation is a joint venture between Chevron and Energy Conversion Devices (ECD) that was formed to focus on developing NiMH batteries and alternative energy processes and products. Chevron Technology Ventures, a subsidiary of Chevron, is involved with identifying, developing, and commercialising new and emerging technologies, including advanced batteries, fuel cells, fuel processing and hydrogen storage. ECD's portfolio of alternative energy technologies includes solar power generation, NiMH batteries, fuel cells and solid hydride storage and the company claims that all significant consumer battery manufacturers worldwide are licensees or affiliates. Cobasys has an agreement with Toyota and its subsidiary, Panasonic EV, to exchange battery technology information. The agreement was reached as part of a legal settlement regarding NiMH battery patents and prevents the two Japanese companies from producing hybrid batteries in the US until 2010.

Continental and Compact Power

General Motors has selected Compact Power of Michigan, USA, and Continental Automotive Systems to develop Li-Ion batteries for its E-Flex battery system, the first of which will be used on the Chevrolet Volt. Compact Power will use batteries produced by its parent company, LG Chem of South Korea, but plans to launch a manufacturing facility in the US during 2009. Continental will source battery cells from A123 Systems, which will supply nanophosphate Li-Ion batteries with an iron-based cathode that is claimed to be more thermally stable than the manganese oxide used in other systems.

Enerize and FiFe Batteries

Enerize Corporation of Florida, USA, and FiFe Batteries of the UK have formed a partnership to develop safe, low-cost, high-energy, Li-Ion batteries for various applications including hybrid vehicles. The companies are focusing on the use of new types of titanium dioxide used by FiFe, high conductivity/high tap density manganese dioxide and low-cost, modified, natural graphite developed by Enerize. These will be complemented by the companies' other proprietary Li-Ion technologies, including electrolyte additives for better cycling stability and a new electrode coating process that will allow the batteries to deliver more power.

Johnson Controls and Saft

Johnson Controls-Saft Advanced Power Solutions (JCS) is a joint venture between Johnson Controls and the French energy storage systems supplier, Saft. The Saft Groupe specialises in the design and manufacture of advanced

batteries for automotive and industrial applications while US-based Johnson Controls provides batteries for traditional and hybrid vehicles, along with systems engineering and service expertise.

In Germany, an alliance that includes BASF, Bosch, Evonik Degussa, Li-Tec, STEAG Saar Energie and Volkswagen has invested around €360m to develop high-performance batteries for consumer goods and automotive applications

During 2006, the USABC awarded JCS a 24-month contract to develop Li-Ion batteries for hybrid-electric vehicles. The project is funded 50:50 by JCS and the USABC. During 2007, JCS announced that it is supplying new, lighter Li-Ion batteries for the Mercedes-Benz S 400 hybrid sedan and Sprinter plug-in hybrid van.

Maxwell and Lishen

Maxwell Technologies and China's leading Li-Ion battery producer, Tianjin Lishen Battery (Lishen), have formed a collaboration to manufacture and market hybrid batteries combining their respective ultracap and Li-Ion battery technologies. The companies claim that their new products can offer the long cycle life, rapid charge/discharge characteristics and low temperature performance of ultracaps and the large energy storage capacity of Li-Ion batteries. Maxwell plans to move some of its product assembly to Lishen, which will conduct development and qualification testing on Maxwell's proprietary battery electrode material. The companies expect to begin production and delivery in early 2008.

Ricardo and QinetiQ

Ricardo and QinetiQ both worked with PSA Peugeot Citroen to develop the Efficient-C Berlingo diesel hybrid demonstrator during 2006, and have more recently embarked on a two-year collaborative project with aims to dramatically reduce the cost and weight of Li-Ion batteries for hybrids while preserving or improving vehicle performance. Currently, the battery system represents around one-third of the incremental manufacturing cost of a typical hybrid vehicle and adds considerably to the vehicle mass. The companies have set a target of producing a new Li-Ion battery with a production cost of around one-third that of conventional battery technologies and around half the weight.

A German alliance

In Germany, an alliance that includes BASF, Bosch, Evonik Degussa, Li-Tec, STEAG Saar Energie and Volkswagen has invested around €360m to develop high-performance batteries for consumer goods and automotive applications. The German Federal Ministry for Education and Research is expected to contribute an additional €60m.

Chapter 9:
Supplier profiles

SUPPLIER PROFILES

Some suppliers of hybrid components focus on one element of the technology while others, such as Delphi and Siemens VDO, offer a broad portfolio that extends to complete hybrid drive system modules. The profiles presented below are of those companies that supply a range of hybrid components, although Aisin Seiki has been included because of its leading role to date through supplying hybrid transmissions to Toyota and other OEMs such as Ford that have licensed Toyota's system.

However, those that essentially supply only batteries and battery management technology should, at least, be mentioned. When Toyota and Honda pioneered the commercial launch of modern hybrid vehicles, the main supplier of NiMH batteries was Panasonic EV, a joint venture created by Matsushita Electric and Toyota in 1996 with the express purpose of developing automotive propulsion batteries.

Currently, Panasonic EV and Sanyo dominate the Japanese hybrid battery supply market through their relationships with Toyota and Honda respectively. However, other companies, including NEC Lamilion Energy, Toshiba and Lithium Energy Japan, a joint venture between Mitsubishi Corporation, Mitsubishi Motors and GS Yuasa, are planning to compete vigorously for market share.

In the US, Continental's relationship with GM places it in a strong position and Delphi and Johnson Controls have also emerged as major players in the hybrid battery market. Compact Power and Cobasys, which also have significant presence in the battery market, have been mentioned above in the section on supplier collaborations. Other companies in the US, such as Altair Nanotechnologies, Electro Energy, Electrovaya and EnerDel, a subsidiary of Ener1, are committing significant R&D efforts towards the development of less costly, more reliable Li-Ion batteries.

Table 13 lists some of the major hybrid component suppliers. Profiles of those highlighted follow.

Table 13: Light vehicle hybrid component suppliers

	Batteries	Electronics	ISAD/BAS	Mechatronics	Motors/Gens	Trans
Aisin Seiki						x
BorgWarner						x
Bosch		x			x	
Cobasys	x					
Continental	x	x	x			
Delphi	x	x	x	x		
Denso		x				
Getrag						x
Hitachi		x				
Infineon		x				
Johnson Controls	x					
Mitsubishi Electric		x				
NEC Lamillion Energy	x					
Panasonic EV	x	x				
Sanyo	x					
Siemens VDO		x	x	x	x	
Toshiba		x				
TRW Automotive			x			
UQM Technologies		x	x		x	
Valeo		x	x			
Visteon		x		x		
ZF Friedrichshafen				x		x

Aisin Seiki

Aisin Seiki is an affiliate of the Toyota Group, with Toyota Motor holding 23% of its shares and Toyota Industries holding 6.9%. It is a global supplier of drivetrain and other automotive products and also has interests in non-automotive areas. During the 2006/07 financial year, its automotive business generated 95.8% of total sales revenue, within which 42.6% was generated by its Drivetrain Products division.

The Drivetrain Products division includes Aisin AW (Aisin Warner), which manufactures automatic transmissions, including six-speed automatics, and Aisin AI, which manufactures manual transmissions. The division also produces CVTs and power-split hybrid transmissions.

Toyota is Aisin Seiki's largest customer, accounting for 67% of sales during the 2006/07 financial year. The company has increased it sales to other OEMs during recent years and major customers include Citroen, Daewoo, DaimlerChrysler, Ford, General Motors, Honda, Isuzu, Mazda, Mitsubishi, Nissan, Suzuki, Toyota, Volkswagen and Volvo. From its strong base with Toyota in Japan, Aisin has been expanding its global operations through substantial investments in China, Europe and North America. It currently has over 140 subsidiaries and 12 affiliates in 19 countries and employs over 59,500 people.

Aisin Seiki's revenue has been growing strongly during recent years and increased 12.2% to ¥2,378.6bn (€15.1bn, 31 March 2007) in 2006/07 compared to ¥2,120.5bn (€14.9bn, 31 March 2006) in the previous year. The Drivetrain Products division's revenue increased 12.5% to ¥1,123.7bn (€7.15bn). Operating profit and net income have also been growing strongly. In the 2006/07 year, operating profit increased 10.9% to ¥131.0bn (€833.2m) from ¥118bn (€ 831.1m) in the previous year and net income increased 9.5% to ¥66.9bn (€425.5m) over ¥61.10bn (€422.6m) in the previous year.

Bosch

The Robert Bosch Group is one of the world's largest automotive components suppliers, with around 280 subsidiaries and 260,000 employees throughout Asia-Pacific, Europe and North and South America. The Group is divided into three main divisions: Automotive Technology, Industrial Technology and Consumer Goods & Building Technology.

The Automotive Technology division generated around 62% of sales revenue in 2006 and is divided into several business units: Automotive Aftermarket, Automotive Electronics, Car Multimedia, Chassis Systems Brakes, Chassis Systems Control, Diesel Systems, Energy & Body Systems, Gasoline Systems, and Steering Systems. The Automotive Electronics division's components include semiconductors, sensors and control units and automotive customers include BMW, DaimlerChrysler, Ford, General Motors, Honda, Nissan, PSA Peugeot Citroen, Renault, Toyota, Volkswagen and Volvo.

The Bosch Group has been pursuing a strategy of broadening its global presence and technical expertise through acquisitions and joint ventures and is also diversifying into several new automotive business areas. The company forecasts that some of the strongest growth for it Automotive Technology division will come from diesel systems and advanced safety systems.

For the financial year ended 31 December 2006, the Bosch Group's consolidated revenue increased 5.4% to €43.7bn from €41.5bn during the previous year. The Automotive Technology division's revenue increased 3.4% to €27.2bn from €26.3bn in 2005, driven by growth in gasoline injection systems, ABS, ESC, electronics and steering systems. The Group's operating income decreased slightly to €2.4bn from €2.5bn in 2005 and net income was also down at €2.2bn from €2.4bn in the previous year. The Automotive Technology division's operating profit fell 28.7% to €1.1bn in 2006 as a result of increases in raw materials prices and reduced demand for the division's products in both Europe and North America as a consequence of downturns in vehicle sales in both markets.

Bosch has forecast a 4% increase in the Automotive Technology division's sales for 2007, excluding the effects of currency exchange rate movements.

Continental

The Continental group has four main business divisions: Automotive Systems, Commercial Vehicle Tires, ContiTech and Passenger and Light Truck Tires. In turn, the Automotive Systems division consists of Continental Temic and Continental Teves, which comprise six business units: Aftermarket, Body Electronics, Chassis & Powertrain, Electric Drives, Electronic Brake and Safety Systems and Hydraulic Brake Systems. During 2007, Continental acquired Siemens VDO (see below) and plans to integrate the acquisition during the next two years in order to realise significant synergies. Prior to the acquisition, Continental employed over 85,000 people worldwide. With Siemens VDO's staff, the group's employee numbers now approach 150,000. In 2006, the Automotive Systems division accounted for over 40% of group sales and employed over 24,000 people.

During recent years, Continental has transformed itself from a tyre and rubber products manufacturer to a systems and modules suppler, largely through the acquisition of ITT Automotive Brake and Chassis and Temic Telefunken Microelectronic in 1998 and 2001 respectively. The group further strengthened its electronic capabilities through the acquisition of Motorola's automotive electronics business and VTI Technologies sensor business in 2006. The division has a goal of becoming a leading supplier of chassis control systems.

For the financial year ended 31 December 2006, Continental's group revenue increased 7.6% to €14.89bn from €13.84bn in 2005. Earnings before interest and tax (EBIT) in 2006 totalled €1.60bn, up 6% from €1.51bn in 2005, and net income increased 5.6% to €981.9m over €929.6m in 2005. The Automotive Systems division's sales increased 14.5% to €5.99bn in 2006, over €5.23bn in 2005. The Automotive division is achieving cost reductions by moving operations to low-cost countries, including Brazil, the Czech Republic, China, Hungary, Mexico, the Philippines, Portugal, Romania and Slovakia.

Delphi

Delphi Corporation was divested from General Motors in 1999 and although it has interests in non-automotive business areas, over 90% of revenue is generated through its automotive business operations. Delphi initially derived more than 80% of its revenue from GM, but has reduced that to around 42% during 2007. Nevertheless, Delphi inherited high employee costs which, combined with difficult market conditions in the US automotive industry led it file for Chapter 11 bankruptcy protection during 2005 in order to restructure, streamline product portfolios, divest unprofitable plants, renegotiate employee benefit entitlements and trade back into viability.

Delphi initially derived more than 80% of its revenue from GM, but has reduced that to around 42% during 2007

At the time of filing for Chapter 11, Delphi had over 300 manufacturing and technical sites globally and around 185,000 employees. However, since then the Corporation has divested several of its operations.

Delphi produces a wide range of automotive products. The company's hybrid vehicle product portfolio includes battery packs, controllers, BAS and ISAD units, stop-start units, power management systems, converters and inverters.

Delphi's sales revenue has declined since the 2004 financial year and in 2006 stood at US$26.39bn, down 2% from US$26.95bn in 2005. The Corporation's operating loss for 2006 was US$4.86bn, more than twice the US$2.17bn loss sustained during the previous year. Similarly, net loss in 2006 was US$5.46bn, compared to US$2.36bn in 2005.

For the first nine months of 2007, revenue totalled US$19.9bn, compared to US$20.0 for the first three quarters of 2006. Net loss was US$2.5bn compared to US$4.6 for the corresponding period of the previous year.

Delphi had planned to exit Chapter 11 protection by the end of 2007, but has sought a delay until 31 March 2008 because of difficulty raising finance.

Panasonic EV

Panasonic EV Energy is a joint venture between Toyota and Matsushita Electric, which markets most of its products under the National brand in Japan and the Panasonic brand elsewhere. Panasonic EV was established in 1996 with the specific purpose of developing and producing NiMH batteries and battery management systems for electric and hybrid vehicles. Currently, the company is focussing on the development of Li-Ion batteries for automotive electric power applications.

Toyota has increased its stake in Panasonic EV to 60% and the joint venture's customers are mostly from the Toyota group including Toyota, Lexus, Daihatsu and Hino hybrid models. The company also originally supplied batteries for the Honda Insight and Civic Hybrid and is expected to supply the forthcoming Hyundai and Kia hybrids. The company has an information sharing agreement with US-based Cobasys, which also produces NiMH batteries.

Financial performance data are not available for Panasonic EV, however, as a joint venture between one of the world's largest automotive OEMs and one of its largest electronics manufacturers, and its position in relation to Toyota's world leading position in hybrid vehicle production and sales, the company seems assured of continuing success in the foreseeable future.

Siemens VDO

Siemens VDO Automotive was formed in 2001 through the merger of Mannesmann VDO and Siemens Automotive and has been until recently the automotive division of Siemens AG. During 2007, Siemens VDO was acquired by Continental Automotive Systems and will be integrated into Continental during the next two years.

Siemens VDO is one of the world's leading suppliers of automotive electronic and mechatronic systems and is organised into nine business areas: Chassis & Carbody; Fleet Management; Infotainment; Interior; Marine Solutions; Special OEM Solutions; Powertrain; Public Transport Solutions and Replacement Parts. It has a global presence in more than 25 countries and employs around 53,000 people. It has been strengthening its position in automotive electronics through acquisitions, including the by-wire specialist, eStop, in 2005. It acquired Ballard Power Systems' electric drive business in 2006.

Its products include: ABS, braking systems, car body electronic systems, chassis systems, cockpits, driver information systems, engine management systems, ESC, fuel injection systems, fuel tank systems, navigation systems, passenger safety systems and powertrain products, including hybrid drive components such as BAS and ISAD units, electronic controllers, inverters, power and energy storage management systems and high-voltage wiring platforms. Its main customers include BMW, Chrysler, Daimler, Fiat, Ford, General Motors, Porsche, PSA Peugeot-Citroen, Renault-Nissan, Suzuki, Toyota and Volkswagen.

For the financial year ended 30 September 2006, Siemens VDO Automotive reported a 4% increase in revenue to €10.0bn over €9.6bn in the previous year. Profit was up 6.2% to €669m from €630m in 2005. The increase in profit reflected cost-cutting and efficiency initiatives and a gain from divestments, offset by increased R&D expenses. For the six months ended 31 March 2007, revenue increased 3% to €2.68bn from €2.61bn in the previous first half. However, profit declined 5% to €169m from €178m.

UQM Technologies

UQM Technologies is a developer and manufacturer of power dense, high-efficiency electric motors, generators and power electronics controllers for the automotive, aerospace, medical, military and industrial markets. UQM places a major emphasis on developing alternative energy products including propulsion systems for electric, hybrid, plug-in and fuel cell vehicles, under-the-hood power accessories and auxiliaries and distributed power generation applications. The company's headquarters, engineering and product development centre, and motor manufacturing operations are located in Frederick, Colorado, USA.

UQM has two business units: the Technology unit develops brushless permanent magnet electric motors, generators, power control technology and software, and offers custom motor design, feasibility studies and full integration services; the Power Products unit manufactures electric motors and electronic products including converters and controllers, and offers computer design, analysis and simulation.

UQM has been involved in the development of several special-purpose hybrid vehicles from concept cars to hybrid Humvees for the US Army to the first Orion hybrid transit bus to go into commercial service

UQM has been involved in the development of several special-purpose hybrid vehicles from concept cars to hybrid Humvees for the US Army to the first Orion hybrid transit bus to go into commercial service. Its hybrid vehicle products include 42-volt ISADs and electrically-powered ancillaries such as air conditioning compressors and fan motors. Alongside supplying several prototype development programmes for hybrids, UQM is supplying Eaton with DC-DC converters for its hybrid truck programme and will be collaborating with Phoenix Motorcars on the development of a plug-in hybrid version of Phoenix's electric pick-up.

For the financial year ended 31 March 2007, UQM reported revenue of US$6.653m, up 57% from US$4.323m during the previous year. Gross profit was US$663,000, up 268% from US$180,000 during the 2005/06 financial year, but the company reported a net loss of $3.431m, compared to a loss of US$2.757m during the previous year. The company stated that its losses increased due primarily to non-cash charges resulting from the adoption of new share-based payment accounting rules.

Despite the losses of recent years, the company is optimistic about the future. Production and product sales volumes are increasing and its order backlog at 30 April 2007 stood at US$16.5m, compared to US$2.2m a year earlier.

Valeo

Valeo is a French automotive supplier that ranks among the top 15 in the world. Its operations are completely focused on the automotive industry and its aftermarket, for which it produces components, integrated systems and modules. Its product portfolio is divided into eleven units: Climate Control (15.5% of 2006 sales), Engine Cooling (15.5%), Lighting Systems (11.9%), Wiper Systems (10.3%), Electrical Systems (10.8%), Security Systems (7.2%), Switches and Detection Systems (8.3%), Transmissions (7.6%) and Electronics & Connective Systems (5.9%), Compressors (4.3%) and Engine Management Systems (3.5%).

Valeo has a global presence with 129 production sites and 68 technical centres in 29 countries and 69,800 employees worldwide. It supplies all major OEMs including BMW, Chrysler, Daimler, Fiat, Ford, General Motors, Honda, Hyundai, Mitsubishi, Navistar, Nissan, Paccar, Porsche, PSA Peugeot Citroen, Renault, Subaru, Toyota, Volkswagen and Volvo Trucks.

Valeo pursues a policy of forming strategic partnerships to facilitate the development of leading-edge products. For example, in partnership with International Rectifiers, the company produces automotive power management electronics such as those used in Valeo's ISADs. A Valeo 42-volt ISAD and thermal systems were used on the i-MoGen demonstrator developed in partnership with Ricardo.

During 2007, Valeo received a research grant of €61m to fund a research programme to develop technologies that will improve fuel efficiency and reduce CO2 emissions. The programme will receive funding of €212m over four years from the Agence de I'Innovation Industrielle and will focus on the development of electromagnetic engine valve actuation and mild hybrid systems.

In the year ended 31 December 2006, Valeo's sales revenue rose 2.3% to €9.97bn over €9.93bn during 2005. However, operating income declined 16.4% to €271m, from €324m in 2005, mainly due to the rising cost of raw materials. Net income increased 13.4% to €161m compared to €142m in 2005, in part because of the divestment of the company's electric motors and actuators business and the sale of a stake in another business.

For the three quarters to 30 September 2007, revenue was up 1.1% to €7.25bn from €7.17bn during the first nine months of 2006 and operating income was up 5% to €231m from €220m.

Visteon

Visteon was spun off from Ford in 1997 and became an independent, listed company in 2000 although in 2006 Ford still accounted for 45% of its sales. It is one of the largest automotive suppliers globally with more than 170 manufacturing, technical and sales facilities in 26 countries. The company's major customers include BMW, Chrysler, Daimler, Ford, General Motors, Honda, Hyundai, Mazda, Nissan, Peugeot, Renault, Toyota and Volkswagen.

Visteon is organised into four business segments: Climate (accounted for 25% of 2006 consolidated sales); Electronics (25%); Interiors (24%); and Other (21%). The company also has unit called Visteon Services (5% of 2006 net sales) that manages the leasing of employees from its wholly-owned subsidiary, Automotive Components Holdings (ACH), to which Visteon transferred its 23 North American facilities in 2005. The company is currently pursuing a restructuring programme and divesting a further 11 facilities.

With its broad expertise in automotive electronics and other automotive systems, Visteon produces control units for power and battery management, mechatronic controls and cooling systems for hybrid motors, batteries and electrical architecture. Visteon supplies several components for the Ford Escape/Mercury Mariner/Mazda Tribute hybrids.

In the financial year to 31 December 2006, Visteon's consolidated sales decreased by 33% to US$11.4bn (€8.6bn, 31 December 2006) compared to US$16.9bn (€14.3bn, 31 December 2005) in 2005. All business units reported lower sales revenue than during the previous year, largely as a result of lower vehicle production volumes by Ford and Nissan. Also, the ACH transactions resulted in a decrease in sales of US$6.1bn (€4.6bn) that was only slightly offset by revenues of US$383m (€290m) for services provided to ACH. Operating income was US$7m (€5.3m) in 2006, an improvement over the operating loss of 66m (€55.73m) in 2005, and net loss improved to US$163m (€123.5m) from a loss of US$270m (€227.9m) in 2005.

For the nine months to 30 September 2007, Visteon's revenue was US$8.408bn, down 0.5% from US$8.448bn during the first three quarters of 2006. The company reported an operating loss of US$119m compared to an operating profit of US$54m during the first three quarters of the previous year and net loss increased to US$329m from US$124m.

Visteon predicts that its restructuring efforts will improve its operating results and forecasts a breakeven outcome for 2008 and a return to profitability in 2009.