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1. Why EVs and Hybrids? - Emissions from Urban Traffic

This paper sets the context for looking at different powertrain architectures and then analyses their relative benefits. The paper focuses on hybrid technologies but also considers hydrogen fuel cells.

Over 14m new cars were registered in Europe in 2007, with average CO₂ emission levels of 158g/ km. The UK figures were 2.35m new cars and average CO₂ emissions of 164g/ km.

The majority of these new cars were in segments C (compact), D (standard-family) and E (executive).

Figure 1. shows the average CO₂ emissions for UK cars sold in 2006¹.

Fig 1. UK cars, average CO₂

The New European Driving Cycle (NEDC) is the European test regime for measuring fuel economy and CO₂ emissions from vehicles. Measurements are taken for urban driving and extra urban driving and then a combined figure is produced. Figure 2 shows the range of speeds measured over time (left: urban peak 45km/h; right: extra urban peak 120 km/h)

Fig 2. NEDC measurement cycle

The fact that the majority of urban motoring worldwide is at very low speeds, creates major problems. Conventional reciprocating engines are much less efficient when operating cold and at low speeds. UK Highways Agency 2007 statistics show very significant increases of CO₂ and regulated emissions at low traffic speeds. (Graphs include an average of 10% Heavy Goods Vehicles).

Fig 3. Pollutants emissions v speed

Fig 4. CO₂ emissions v speed

¹ Source: DfT
UK DfT 2007, statistics show that average morning peak (6:30 – 9:30am) speeds on key routes in the ten largest urban areas vary considerably from route to route and area to area, with 5 per cent of routes achieving average speeds in excess of 30 mph (48 km/h), and 38 per cent with average speeds of 15 mph (24 km/h) or lower. Studies from across Europe show similar findings. A survey commissioned by Citroën, published in Aug 08, looked at morning rush hour traffic congestion in five major city centres: London, Cardiff, Birmingham, Norwich and Manchester. The results showed that the average driver was stopped for 25 minutes of the average hour-long commute, in which they travelled just 12.9 miles.

Given this level of UK traffic delays and the data from fig. 3 and fig. 4, it is reasonable to infer that about a quarter of the UK’s peak hours traffic is emitting over 500 g/km CO₂, more than 5 times average carbon monoxide levels and nearly 3 times average Nitrous Oxides levels.

According to the European Commission’s statistics body Eurostat, the passenger mobility data for Europe are broadly similar to the US. A summary compiled by Eurostat in 2007 of the most recent national travel surveys found that people in most countries make on average three trips per day, totalling between 30 and 40 km across all modes of transport. These passenger kilometres are predominantly satisfied by the use of private cars: in the EU-25, close to 460 million citizens travel a daily average of 27 km by car. Taking a specific national example, we find that in 2002/03 more than three quarters of car journeys in the UK were less than 10 miles (16 km) in length, while a massive 93% were below 25 miles (40 km).

These facts set the context and the drivers for reducing emissions from vehicle powertrains. The primary objective needs to be: reduce CO₂ and pollution from slow speed, short distance traffic. As set out in the accompanying document “Low Emission Powertrain Market Analysis” this paper finds that the most cost effective method of achieving this objective for private cars, is through the development of hybrids (HEVs), plug in hybrids (PHEVs) and electric vehicles (EVS).

It is sometimes claimed that EVs just displace the problem of CO₂ emissions to the power stations and that given inefficiencies in producing and distributing electricity, that the overall well-to-wheels emissions of EVs are greater. In the report “Plugged-in: the End of the Oil Age”, (WWF, 2008) Dr. G. Kendall shows that given the current EU electricity generation mix, and conservative estimates about the efficiency of battery electric vehicles (BEV) compared to an ICE powered vehicle, W-T-W savings of over 57% CO₂ emissions are possible by an EV or a plug-in hybrid operating in EV mode (619g : 1460g / kWh (average of gasoline and diesel ICE)).

As electricity generation becomes cleaner (e.g. increased share of renewable energy), W-T-W emissions from EVs reduce. As these cars get older they will become cleaner; while the opposite is true for conventional internal combustion engine (ICE) vehicles.
The Review of the UK Innovation System for Low Carbon Road Transport Technologies, by E4 Tech March 07, for the DFT, found that,

"All-electric vehicles may be a viable option for consumers who require a car for short urban journeys only but these vehicles do not yet possess the range, size or top speeds likely to make them attractive for the majority of consumers. Significant battery advances would be required to allow electric vehicles to achieve mass market commercialisation and many view the development of plug-in hybrids, which can potentially combine the lower emissions of electric vehicles with improved range and performance, as an alternative route to widespread use of electricity in vehicles."

Figure 6. and 7 show comparisons and development stages of hybrid technologies."

---

**Fig. 6** Comparison of hybrid technologies

![Comparison of hybrid technologies](image1)

**Fig. 7** Development stages of hybrid technologies

![Development stages of hybrid technologies](image2)
2. Analysis of Hybrid Strategies

The IBM Global Business Services Report (Aug 08), “Automotive 2020: Clarity Beyond the Chaos” predicts that by 2020, all new vehicles will have some level of hybridisation. Micro, mild and full hybridisation is undergoing extensive development. The following gives a brief explanation of the key features of different hybrid architectures. It should be noted that there is considerable cross over between these types in the manufacturing solutions being developed, so they should not be regarded as clear and distinct categories.

Micro-hybrids

Micro hybrids, also known as ‘stop-start’ systems save fuel and emissions by shutting engine power off under most circumstances when the vehicle is stopped, braking, or coasting. Batteries or ultracapacitors are sometimes used to recover kinetic energy otherwise wasted when braking, known as "regenerative braking".

Mild Hybrids

A mild hybrid is a type of gasoline-electric hybrid that incorporates an electric motor as a power booster of sorts, as a starter-generator, or both. The electric drive motor cannot ever propel the vehicle on its own. Mild hybrids also save fuel and emissions by shutting engine power off under most circumstances when the vehicle is stopped, braking, or coasting. All mild hybrids are less expensive than full hybrid systems because they require less sophisticated components and less battery power. Some, but not all, mild hybrids use regenerative braking to recharge the battery. Different mild hybrid configurations exist including Integrated Starter-Generator (ISG) and Belt Alternator Starter (BAS) systems.

Although they do not offer the all-out benefits of full hybrids, mild hybrids do provide a modest improvement in fuel efficiency of 10 to 15 percent because they’re not burning gasoline when stopped. Because they are less costly than full hybrid systems, this easy entry into the world of hybrids can serve to familiarise drivers with hybrid technology and potentially encourage drivers to choose a full hybrid for their next vehicle.

Fig 8. Mild hybrid fuel and emissions saving features
Full Hybrids

Examples of full hybrids (also known as two/dual mode hybrids) are the Toyota Prius and the Ford Escape. A full hybrid is a vehicle that utilizes all of the advantages of hybrid technology. A full hybrid is capable of moving under electric power only. It can drive off without the engine running. Since this feature is normally employed when accelerating from a complete stop (engineers refer to this as the launch mode) a full hybrid will feature electric launch. During electric launch, the vehicle is completely quiet. A full hybrid also features regenerative braking and the engine stop or idle stop feature.

Engine stop combined with regenerative braking are the main reasons why most hybrids actually achieve better fuel economy in city/urban driving than during highway driving. Hybrid drivers will notice how rapidly the engine restarts. The conventional 12-volt starter motor that has been used to start automobile engines for nearly a century can only spin the engine up to a speed of approximately 250 RPM. The high-voltage integrated starter/generator (ISG) of a hybrid will spin the engine at speed in excess of 900 RPM. This assures an almost instantaneous restart (less than 300 milliseconds) of the hybrid engine.

Finally, a full hybrid will feature a downsized internal combustion engine. A conventional automobile must obtain all of its power from its internal combustion engine. This engine must be sized appropriately to be able to provide adequate acceleration and the ability to climb steep grades. Because a hybrid can call upon the electric traction motor to provide additional power to the wheels when needed, such as during rapid acceleration or climbing steep grades, the internal combustion engine can be downsized. In a hybrid, the internal combustion engine need only be able to supply the average horsepower demand of the vehicle. Use of a smaller engine with energy-efficient operating strategies such as the Atkinson Cycle also helps to improve the efficiency and fuel economy of hybrids.

Fig 9. Illustration of full hybrid driving cycle
Plug In Hybrids

Electric motors are 90-95% efficient compared to gasoline engines (30%) and diesel engines (40%). A vehicle powered by an electric motor delivers maximum torque from a standing start and produces zero local emissions. On reflection, it should be a ‘no brainer’ to conclude that the optimum powertrain strategy is to configure the electric motor as dominant, with the ICE in support! Why haven’t OEMs done this already? Mainly because of vested interests, inertia and cost issues.

The US Energy Independence and Security Act of 2007 defines a plug-in electric drive vehicle as a vehicle that:

- draws motive power from a battery with a capacity of at least 4 kilowatt-hours;
- can be recharged from an external source of electricity for motive power;
- is a light-, medium-, or heavy-duty motor vehicle or nonroad vehicle.

This distinguishes PHEVs from regular hybrid cars mass-marketed today, which do not use any electricity from the grid.

The Institute of Electrical and Electronics Engineers (IEEE) defines PHEVs similarly, but also requires that the hybrid electric vehicle can drive at least ten miles (16 km) in all-electric mode (PHEV-10 / PHEV16km), while consuming no gasoline or diesel fuel.

The figure below is an illustration of the AFS Trinity conversion of a GM Saturn Vue SUV, which reportedly will use a low cost battery pack, supplemented by ultracapacitors to aid acceleration.
Plug in hybrids achieve the primary objective of reducing CO₂ from slow speed, short distance traffic, while avoiding the range limitations of pure electric vehicles.

As explained in the document ‘Low Emission Powertrain Market Analysis’, the battery for a plug in hybrid only needs to be sized to meet the average daily driving requirements (US 30 miles, Europe 30 km). This can significantly reduce the purchase price of a PHEV compared to an EV.

Beyond the plug in hybrid’s EV range, the vehicle must revert to relying on the conventional ICE for the main source of power, however this is what the ICE is best suited to anyway. The plug in hybrid takes maximum advantage from both powertrain options – zero pollution driving in urban areas, with no compromise in high speed, long distance driving.

The California Cars Initiative (CalCars.org) - a non-profit group encouraging auto makers to produce 100+MPG, high-performance, clean hybrid cars – has conducted, commissioned and analysed extensive research, including producing several demonstration plug in hybrids. Therefore the CO₂ emissions reductions charted below can be considered authoritative for the US.

![Fig 12. CO₂ emissions reductions from hybrids](image)

**Series – Parallel Debate**

On a technical subject, there is an interesting debate on how best the hybrid powertrain components should best be configured. The two main options are: a series topology where the internal combustion engine (ICE) is connected in series to the generator-battery-electric motor and is not directly connected to the driveshaft; and a parallel topology where the ICE is in parallel with the electric motor and can directly connect to the driveshaft (which goes to the wheels via the transmission (gearbox)). A series-parallel topology includes the capability for the ICE to simultaneously power the driveshaft and recharge the battery.

![Fig 13. Series – Parallel Hybrid Options](image)
This debate is best represented by the different approaches being taken by GM for the Chevrolet Volt (series) and Toyota for the next generation Prius (series-parallel). The two approaches are more graphically illustrated by figure 14. below (produced by Toyota).

Within the series architecture, the battery tends to be larger (Volt = 16 kWh, 40 mile range, 90% < > 40% state of charge (SOC)) the electric motor tends to be larger (Volt = peak power 140kW, 180HP) and the ICE tends to be smaller (Volt = 1.4L, 53kW, 71 HP).

Within the parallel and series-parallel architecture the battery is smaller (Prius gen 3 = 4kWh, 9 mile range, 90% < >30% SOC), the electric motor is smaller (Prius gen 3 = peak power 50kW, 67HP) and the ICE tends to be larger (Prius gen 3 = 1.8L, 70kW, 94HP).

As various commentators and analysts have pointed out, both approaches have advantages depending on the driving cycle. As noted in figure 6. at the point where a series hybrid has exceeded its EV range and is relying on the ICE to turn the generator, to create electricity, which is then converted back into mechanical energy by the motor to turn the driveshaft; there is about a 15% loss of efficiency. In this scenario a parallel topology is more efficient since there is only about a 5% loss of efficiency from the ICE directly turning the driveshaft via the transmission.

A series topology does not require a transmission (i.e. there are no gears) because of the torque characteristics and wide rpm range of electric motors. Due to the larger motor and battery, a series topology can deliver full performance (including improved acceleration) in EV mode alone, whereas a parallel topology requires a combination of the ICE and the electric motor to achieve this. In this respect a series hybrid is ‘cleaner’ and will be likely to produce less CO₂ and pollution within urban environments. Over longer distances, in highway traffic a parallel topology is likely to
be cleaner. In terms of the primary objective we have defined: to reduce CO₂ and pollution from slow speed, short distance traffic, both solutions deliver this.

Considering that about 80% of daily driving distances are below 50 (miles US / Km Europe); within the EV range of PHEVs; the simplicity, efficiency and zero urban emissions of the series topology approach is particularly attractive. However the major drawback to this, is the extra cost of larger, advanced batteries.

Felix Kramer, the CEO of CalCars concludes, “Then, eventually—as batteries become a cheaper, longer-life, commodity item, liquid fuels become more dear, renewable electricity generation proliferates, and CO₂ emissions are increasingly targeted—the PHEVs with the most EV power and range will come to dominate”

3. The Connected Vehicle

The document “Low Emission Powertrain Market Analysis” provides more information about the concept of ‘the connected vehicle’ however the key features of this are:

- The vehicle can be connected to the electricity grid to recharge
- The vehicle can store and return electricity to the grid (V2G)
- The vehicle can connect to electrical equipment or AC circuits, acting as a mobile generator or uninterrupted power supply
- The vehicle can connect to the internet for a wide range of communication and entertainment functions
- The vehicle can connect to the satellite network for GPS and data monitoring purposes

The key attribute of the connected vehicle is its flexibility and the development of wheel motors allows even greater possibilities. Figure 16 below shows the platform of a Volvo concept car.

Wheel motors are currently prohibitively expensive for commercial applications but examples such as the Volvo Re-charge, demonstrate the potential for: further increased efficiency (no driveshaft); fully electronic regenerative braking; and increased flexibility in the use of space within the vehicle. Some technical issues need to be overcome, such as increased unsprung weight and susceptibility to vibration and water, but these are not insurmountable. This kind of innovation greatly assists the ability to modularize production of vehicles, enabling completely different models to be assembled on the same production lines, thereby reducing costs.
4. Modes of operation

Regardless of its architecture, a plug-in hybrid may be capable of charge-depleting and charge-sustaining modes. Combinations of these two modes are termed blended mode or mixed-mode. These vehicles can be designed to drive for an extended range in all-electric mode, either at low speeds only, or at all speeds. These modes manage the vehicle’s battery discharge strategy, and their use has a direct effect on the size and type of battery required:

**Charge-depleting mode** allows a fully charged PHEV to operate exclusively (or depending on the vehicle, almost exclusively, except during hard acceleration) on electric power until its battery state of charge is depleted to a set level, at which time the vehicle’s internal combustion engine (ICE) will be engaged. This provides the vehicle’s EV range. This is the only mode that a battery electric vehicle can operate in, hence their limited range.

**Blended mode** is a type of charge-depleting mode normally used by vehicles which do not have enough electric power to sustain high speeds without the help of the ICE. A blended control strategy increases the range under at least partial battery power, compared to the charge-depleting mode.

**Charge-sustaining mode** is used by current hybrids such as the Toyota Prius. Over the course of a journey, the state of charge of the battery may fluctuate but will have no net change. Because the battery of a current Prius cannot be plugged in to be charged, it only temporarily ‘holds’ energy recovered from regenerative braking or generated by the ICE.

**Mixed mode** describes journeys in which a combination of the above modes are used. For example, a PHEV-20 (20 mile EV range) may start with 5 miles of low speed charge-depleting mode, then join a highway and operate in blended mode for 20 miles using 10 miles worth of all-electric range. Finally the driver might exit the highway and drive for another 5 miles without the ICE, until the full 20 miles of all-electric range are exhausted. At this point the vehicle can revert back to a charge sustaining-mode for another 10 miles until the final destination is reached.

![Fig 17. PHEV modes of operation](image)

![Fig 18. Cutaway of Chevrolet Volt, showing engine generator and battery pack over driveshaft](image)
5. Battery Power, Energy Density & Cost

For the future evolution of hybrids, plug-in hybrids and electric vehicles, the key technological challenge is generally considered to be the development of battery technology, which delivers greater energy density and power density, at acceptable cost to the consumer. Greater energy density means that the battery can 'hold' more energy to achieve longer journeys (measured in Wh/kg & Wh/l). Greater power density means that the battery can deliver higher voltage x ampage for acceleration and hill climbing / towing loads etc (measured in Wh/l & W/kg).

Nickel-metal hydride (NiMh) batteries are the most popular in current commercial hybrids but are generally expected to be replaced by lithium-ion (Li-ion) in future models from the end of this decade onwards. Figure 19. compares the energy density, power density and typical costs of different battery types2. (NB: costs vary significantly between manufacturers)

![Figure 19. Energy density / power density / cost of batteries](image)

Lithium Iron Phosphate (LiFePO₄) chemistries are currently considered the best battery solution by many, since they do not have the overheating problems associated with some lithium ion chemistries. The world's largest producer of Li-ion batteries (including LiFePO₄) is BYD (China), who is also a car manufacturer and plans to use Lithium Iron Phosphate batteries to power its own PHEV, the F3DM and F6DM (Dual Mode). It plans to mass produce the cars in 2009, which will make it the first plug-in hybrid vehicle on sale in the world. Aptera Motors also plans to use this battery chemistry for their electric/hybrid vehicle, the Aptera Typ-1.

However, when cost is considered, bi-polar lead acid batteries present a real alternative which is largely overlooked. Bi-polar lead acid batteries have much lower volume and weight than conventional lead acid batteries due to the way the plates are constructed and stacked within the battery. They are no more expensive to produce than conventional lead acid batteries.

Comparing bi-polar Lead Acid (b-p PbA) and Lithium Iron Phosphate (LiFePO₄) batteries it can be seen that b-p PbA batteries have about 33% of the energy density and 30% of the power density of LiFePO₄ batteries, however they cost about 11% of the price! When considering whether b-p PbA batteries are a viable alternative to Lithium chemistries it is critical to investigate what the power requirements of PHEVs actually are. The key considerations are whether the battery is too heavy to be feasible for regular use, whether it is too bulky to be accommodated easily within the vehicle, whether it has enough power density to provide sufficient acceleration / hill climbing / towing power and whether it has sufficient life cycle durability to provide reliable long term use. (NB: GM has set Continental (DE)/ A123 Systems (US) and Compact Power / LG Chem (S. Korea) 10 year battery life targets for the Chevrolet Volt).

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2 Sources: www.axeonpower.com; Ricardo submission to UK King Review, Sep 07; www.gm-volt.com; Deutsche Bank report ‘Electric Cars: Plugged In’, Aug 08, correspondence with Atraverda Sep 08.
6. Power Requirements of a PHEV

The power requirements of a vehicle can be reasonably estimated using the following formula:

\[
P_{\text{mot}}(\text{gradient}, v) = \frac{P_r(v) + P_{\text{air}}(v) + P_{\text{grad}}(\text{gradient}, v)}{\eta_{\text{mech}}}
\]

Rolling resistance:
\[
P_r(v) = c_r \cdot m_{\text{max}} \cdot g \cdot v
\]

Air drag:
\[
P_{\text{air}}(v) = c_d \cdot A_f \cdot 0.5 \cdot \zeta \cdot v^3
\]

Gradient demand:
\[
P_{\text{grad}}(\text{gradient}, v) = m_{\text{max}} \cdot g \cdot v \cdot \sin(\arctan(\text{gradient}/100))
\]

Velocity:
\[
v
\]

Mechanical efficiency:
\[
\eta_{\text{mech}}
\]

(with the following constants and assumptions)
- Gravitational acceleration: \( g = 9.81 \, \text{m/s}^2 \)
- Air density at 1 bar and 20 °C: \( \zeta = 1.19 \, \text{kg/m}^3 \)
- Tyre rolling coefficient: \( c_r = 0.01 \)
- Drivetrain efficiency: \( \eta_{\text{mech}} = 0.98 \) (PHEV does not need a gear box)

Taking the example of the Chevrolet Volt, from the GM released specifications:
- Height = 1.336m; width = 1.791m = vehicle frontal projected area = 2.153m²
- \( C_d \) (estimate) = 0.3
- Weight = car = 1,596kg, fuel = 47kg, family of four = 207kg = 1,850kg (= average car)

Figure 20. shows the power requirements of the vehicle on different gradients (NB: 4% incline is the maximum for UK motorways). Since the electric motor has a maximum continuous output of 45kW, this is shown in red as the limit of performance over long periods of time, however this can be easily exceeded for short durations. On flat roads, the power required to keep the car moving at about the 30mph speed limit in built up areas, is about 5kW (13HP)! Set against average ICE engine powers of 100HP, this illustrates how inefficient our current ICE technology is.
7. Battery Requirements (cont’d)

Returning to the discussion of battery requirements, we can examine more closely whether bi-polar lead acid batteries could meet the requirements of a PHEV at a much lower cost.

**b-p PbA Battery too heavy?** Using Calcars demonstration vehicles results which show PHEVs require about 0.26kWh per mile in normal driving conditions\(^3\); a battery with a 4 kWh (5 kWh @80% discharge) capacity would deliver a 15.4 mile EV range (24.75 km); which is just under the European average daily driving distance of 27km. Since demonstration b-p PbA battery packs have specific energy (energy density) of 53Wh/ kg\(^4\), and can operate with a state of charge 100% < > 20%, we find that a 100kg battery pack would be needed.

The Chevrolet Volt 16 kWh battery pack weighs 180kg, therefore we can reasonably estimate that an 8 kWh battery pack would weigh 90kg. Lithium based batteries are not tolerant of overcharging and to minimise battery degradation and ensure at least 10 years lifespan, the battery is being oversized by 100% (state of charge likely 90% < > 40%). Therefore to provide 4kWh of driving capacity, the battery needs to be 8kWh in total. Although the energy density of Lithium phosphate is about 150Wh/kg\(^4\), meaning that the battery cells for this capacity would weigh only 54kg, lithium phosphate cells also require sophisticated liquid cooling and battery management systems. The extra weight of these systems leads to a total pack weight of 90kg. Therefore we find that a b-p PbA pack could deliver the same performance as a lithium phosphate pack for only 10 kg more (!)

**b-p PbA Battery too bulky?** Using the figures above, and given the energy density of 105 Wh/ l, we find that the b-p PbA battery pack would have a volume of about 55 l. The Chevrolet Volt’s battery pack is about 100 l and therefore an 8kWh pack would occupy 50 l – only 5 litres less (!)

**b-p PbA Battery not enough power density?** Using the example of the Chevrolet Volt again, the maximum power specified is 140kW, with an operating Voltage of 320V – 350V; therefore it can be seen (Voltage x Amps = Watts) that the maximum Ampage is about 400A. In the urban driving example above, 0-30mph in 3-4 secs, would require about 234A. This is beyond the range of current b-p PbA battery packs, which can only deliver about 100A. As in the example of the AFS Trinity SUV, figure 11. a supplementary power source would be required such as ultracapacitors. (NB: an ultracapacitor is a double layer electrical capacitor which stores energy in an electro-static charge rather than in chemical form as in batteries. This allows higher power density, but with much lower energy density and very high life cycle duration). An ultracapacitor pack only needs to deliver very short bursts of energy (10 secs) therefore a capacity of only about 0.2 kWh is required (weight about 6kg). At current prices, a pack of this size would cost about £550\(^5\).

**b-p PbA Battery not sufficient life cycle durability?** b-p PbA batteries tend to have a duration of about 1,000 charge-discharge cycles (at 80% discharge). This is significantly lower than for Lithium ion chemistries which appear to achieve 3,000 - 7,000 cycles. Given almost daily use, a b-p PbA battery pack would probably fail after about 3 years. The point is that if the battery pack only costs about £250 this does not matter! It can be cheaply replaced!! In the examples given a 5 kWh b-p PbA battery pack with a 0.2 kWh ultracapacitor pack would cost about £800, compared to a Lithium phosphate pack of £3,200, which represents a saving of 75%.

UK companies such as Atraverda are developing bi-polar lead acid batteries, as well as others around the world such as Firefly (US) and Effpower (Sweden). Companies such as Furukawa (Japan) / CSIRO (Aus) are developing ‘Ultrabatteries’ which integrate low cost / high power density components and breakthroughs in increasing the energy density of ultracapacitors are being reported by companies such as Eestor (US). The US Automotive Battery Consortium (USABC) has set a price target for Lithium based batteries of $500 (£285) / kWh.

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\(^3\) PHEV fuel economy in EV mode = 0.26kWk / mile; supported by various US studies

\(^4\) Source, Atraverda

\(^5\) Source US NREL, 2007
8. Hydrogen Fuel Cells

The E4 Tech report makes the following observations about hydrogen fuel cells.

“Hydrogen and fuel cell technologies face a number of technical and cost challenges before they can become commercially viable options for road or other transport modes. Fundamental fuel cell stack performance is not yet able to deliver the required mix of power density, lifetime, cold start and other properties at acceptable cost. Even if the impact of scale economics is considered, fuel cells currently cost significantly more than the long term cost targets necessary for volume manufacture for mass markets. … In addition, for both fuel cell vehicles and hydrogen powered internal combustion engines, on board hydrogen storage does not yet provide an acceptable range for most vehicles in conventional applications. Hydrogen storage requires basic and applied research and development, depending upon the option under investigation.”

Dr. Ulf Bossel of the European Fuel Cell Forum concludes:

“Without the slightest doubt, the technology for a hydrogen economy exists or can be developed in reasonable time. Also, hydrogen is an appropriate energy carrier for particular niche applications, or it may become an important medium for electricity storage with reversible fuel cells. But hydrogen can never establish itself as a dominant energy carrier. It has to be fabricated from high grade energy and it has to compete with high grade energy in the market place.

Physics is eternal and cannot be changed by man. Therefore, a “Hydrogen Economy” has no past, no present and no future. The road to sustainability leads to an ‘Electron Economy’.”
9. It still comes back to the engine

The diagram below illustrates the full range of energy losses from a conventional vehicle. Scenario a) illustrates these losses at low traffic speeds (urban) and scenario b) illustrates higher speeds (extra-urban). “Driveline” in this illustration represents the vehicle transmission (gear box), driveshaft and axle differential.

It can be seen that including standby, the conventional engine is typically only 21% efficient in urban traffic. In motorway traffic the conventional engine is still only 27% efficient. Of course this is the whole point of developing the hybrid architecture of PHEVs so that particularly in urban traffic, the efficiency of the powertrain can be raised to 80%+.

However even in a plug in hybrid it can be expected that the conventional engine (ICE) will be required for about 50% of the time, either to power the generator, or to turn the driveshaft directly.

Therefore the energy efficiency of the vehicle still depends critically on the efficiency of the engine.

Fig 21. Energy losses from vehicle in urban and motorway traffic

It has already been noted that when an engine operates as a generator, it can be set to near its optimum efficiency point, irrespective of the vehicle acceleration and deceleration. Diesel engines are generally regarded as more efficient than gasoline engines; so the ideal should be a diesel generator.

Figure 22. shows the efficiency of several small diesel generators plotted. It can seen that the diesel generator is still only reaching about 36% efficiency.

Fig 22. Small Diesel Generator Efficiencies

The E4 Tech report for the DfT (2007) notes that in relation to engine development. “The nature of innovation in this area is that the more far sighted innovation is generally not performed by the OEM vehicle manufacturers (although they may participate by donating materials and outcome and observing the outcome). Instead it usually comes from research consultancies and universities, where OEMs only tend to become more heavily involved at the demonstration vehicle stage and beyond.” The development of the Libralato rotary engine is such an example.
The document “Libralato Engine Technical Summary” provides an explanation of how the Libralato engine works and how it can deliver about a 10% efficiency gain compared to equivalent gasoline or diesel engines.

Figure 24 shows an exploded view of the principal engine parts.

Figure 25 plots this efficiency gain compared to state-of-the-art gasoline and diesel engines and a PEM Hydrogen fuel cell.
The Review of the UK Innovation System for Low Carbon Road Transport Technologies, by E4 Tech, March 07, indicates where the most significant powertrain developments are likely to occur in the next 20 years.

![Fig. 26 E4 Tech predictions of engine innovation 2005 - 2025](image)

The development of the Libralato engine realises one of the key predictions of the review. It is a rotary engine with only four moving parts which perform the four phases in every revolution of the engine. Therefore double the work per cycle is extracted and this work does not need to be converted from linear motion into rotary motion. The engine has a unique, asymmetrical compression and expansion geometry which could deliver a step change in thermal efficiency. The engine’s unique, integral exhaust gas recirculation could deliver a step change in cleansness. The main advantages of the engine are:

1. Exceptionally simple design leading to lower production and maintenance costs
2. Double the power to weight ratio of a reciprocating engine; compact shape
3. Approximately 33% more efficient than conventional 4-stroke engine (i.e. approx 40% efficient with gasoline compared to 30% efficient 4-stroke engine; approx 50% efficient with diesel compared to 40% efficient 4-stroke engine)
4. At least 5% greater mechanical efficiency / low vibration due to rotary design
5. At least 5% greater thermal efficiency due to asymmetrical expansion and compression volumes (~Atkinson cycle)
6. Lower emissions due to recirculation of exhaust gas, integral to engine cycle (NOx <50%)
7. Silent and low temperature exhaust gases due to low exhaust pressure
8. Good sealing and thermal dispersion characteristics, avoids problems of Wankel engines
9. Geometry easily adaptable for biofuels (ethanol and biodiesel)

Use of a Libralato engine-generator within a plug in hybrid could provide a real breakthrough in terms of optimising a low carbon, low cost approach:

- Libralato engine can deliver the same efficiency as a diesel engine using lower cost gasoline
- Libralato engine produces the same power for approximately half the size and weight (power phase every revolution)
- reduced production costs of engine due to 23% fewer parts
- reduced battery costs due to weight and space savings
- reduced vehicle bodywork redesign due to compact engine size

![Libralato engine asymmetric geometry](image)
The E4 Tech review for DfT (2007) summarises the emissions gains of the different hybrid strategies, based on information supplied by the Institut Francais du Petrole (2005) and from Ricardo (2007). A plug in hybrid has been added to the table based in the results produced by CalCars. A PHEV using a Libralato engine-generator has also been added to the table, which demonstrates the 10% advantage of the engine in both gasoline and diesel versions.

<table>
<thead>
<tr>
<th></th>
<th>Electric Power kW (continuous)</th>
<th>Typical CO₂ emission savings (urban)</th>
<th>Typical CO₂ emission savings (complete drive cycle)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Micro Hybrid</td>
<td>2</td>
<td>8%</td>
<td>4%</td>
</tr>
<tr>
<td>Mild Hybrid</td>
<td>10</td>
<td>30%</td>
<td>20%</td>
</tr>
<tr>
<td>Full Hybrid</td>
<td>30</td>
<td>45%</td>
<td>30%</td>
</tr>
<tr>
<td>Plug in Hybrid</td>
<td>45</td>
<td>90%</td>
<td>40%</td>
</tr>
<tr>
<td>Libralato engine PHEV</td>
<td>45</td>
<td>93%</td>
<td>50-60%</td>
</tr>
</tbody>
</table>

Fig 28. Hybrid strategies - CO₂ reduction comparison

The European Automobile Association (ACEA) has estimated that meeting the proposed 130g/km EC CO₂ limit by 2015 will add £2,380 (€3,000) to the price of each vehicle, for approximately a 25% emissions saving.

In submissions to the UK King Review of Low Carbon Cars (2007), Ricardo estimated the costs of different powertrain strategies, relative to CO₂ reductions. A PHEV using a Libralato engine-generator has been added to this graph using the same standardised costs for hybrid vehicle components, but including the assumptions:

1) In a series hybrid topology the engine can be significantly down-sized
2) The battery size for a segment C-D PHEV only needs to be 5 - 8 kWh
3) A much lower cost (b-p PbA -Ultracapacitor) energy storage pack could be used

The range shown includes use of low cost / higher cost battery options.

Fig 29. low carbon – low cost of Libralato engine
10. Conclusion

The document “Low Emission Powertrain Market Analysis” shows that UK consumers expect to pay about £3,000 ($5,250) more for a hybrid, which they assume will deliver CO2 and fuel cost savings of about 25%. This is slightly higher than the European average and the European Automobile Association’s (ACEA) estimates that a 25% increase in efficiency will add about £2,380 ($3,860) to the cost of a vehicle. Use of a Libralato engine-generator within a plug in hybrid can deliver 50% - 60% efficiency improvements (complete drive cycle), but is the extra capital more cost effective?

The Deutsche Bank report ‘Electric Vehicles: Plugged In’ benchmarks the extra costs of different hybrid and EV architectures and plots them against predicted efficiency gains (NB: fuel efficiency very dependant on driving cycle).

<table>
<thead>
<tr>
<th>Battery Cost</th>
<th>Incremental Cost</th>
<th>Total Cost</th>
<th>Efficiency Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Micro Hybrid</td>
<td>$100</td>
<td>$500</td>
<td>$600</td>
</tr>
<tr>
<td>Mild Hybrid</td>
<td>$600</td>
<td>$1,000</td>
<td>$1,600</td>
</tr>
<tr>
<td>Full Hybrid</td>
<td>$1,200</td>
<td>$1,000</td>
<td>$2,200</td>
</tr>
<tr>
<td>PHEV</td>
<td>$6,000</td>
<td>$2,000</td>
<td>$8,000</td>
</tr>
<tr>
<td>Electric Vehicle</td>
<td>$11,000</td>
<td>$0</td>
<td>$11,000</td>
</tr>
</tbody>
</table>

* = Incremental costs offset by elimination of ICE and other components

Source: Deutsche Bank

Fig. 29 Cost Effectiveness of (H)EV architectures

The following table, uses the Deutsche Bank / American Council for an Energy Efficient Economy (ACEEE) figures, and adds a PHEV15, use of a Libralato engine generator and use of bi-polar lead acid batteries.

<table>
<thead>
<tr>
<th></th>
<th>Micro Hybrid</th>
<th>Mild Hybrid</th>
<th>Full Hybrid</th>
<th>PHEV 40</th>
<th>PHEV 15</th>
<th>Libralato PHEV 15</th>
<th>Libralato PHEV 15 b-p pBA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery $ / kWh</td>
<td>600</td>
<td>600</td>
<td>600</td>
<td>500</td>
<td>500</td>
<td>500</td>
<td>90</td>
</tr>
<tr>
<td>Battery kWh</td>
<td>0.16</td>
<td>1.0</td>
<td>2.0</td>
<td>12.0</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Ultracapacitors</td>
<td>0.2kWh</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.2kWh $965</td>
</tr>
<tr>
<td>Battery total cost $</td>
<td>100</td>
<td>600</td>
<td>1200</td>
<td>6000</td>
<td>2500</td>
<td>2500</td>
<td>1415</td>
</tr>
<tr>
<td>Other incremental costs $</td>
<td>500</td>
<td>1000</td>
<td>1200</td>
<td>2000</td>
<td>1800</td>
<td>1400</td>
<td></td>
</tr>
<tr>
<td>Total incremental costs $</td>
<td>600</td>
<td>1600</td>
<td>2400</td>
<td>8000</td>
<td>4500</td>
<td>4300</td>
<td>2815</td>
</tr>
<tr>
<td>Annual fuel savings $</td>
<td>472</td>
<td>944</td>
<td>1526</td>
<td>2070</td>
<td>1892</td>
<td>2082</td>
<td>2082</td>
</tr>
<tr>
<td>Pay back period yrs</td>
<td>1.3</td>
<td>1.7</td>
<td>1.6</td>
<td>3.9</td>
<td>2.4</td>
<td>2.1</td>
<td>1.4</td>
</tr>
</tbody>
</table>

Assumptions made by Deutsche Bank / ACEEE:

| Cost of fuel in Europe | $8.50 (/US gallon) = £1.28 / l |
| Cost of electricity per / kWh | $0.1 |
| Average miles per annum | 10,000 |
| PHEV Assumptions | PHEV 40 = 6,667; PHEV 15 = 5,613 |
| Miles driven EV | PHEV 40 = 3,333; PHEV 15 = 4,387 |
| Fuel Economy ICE | 30 (/US gallon) |
| Fuel economy HEV | 45 (/US gallon) |
| Fuel economy Libralato HEV | 58.5 (/US gallon) |
| Fuel economy Full Hybrid | 65 (/US gallon) |
| Fuel economy EV | 5 (miles per kWh) |
It’s important to qualify that these scenarios relate to Europe, where the cost of gasoline is more than twice that of America. They are also relative to a (not too distant?) oil price of $140/bbl and a Li-on battery price of $500 / kWh. It should also be noted that the fuel economy of EVs is perhaps overestimated, since many US government studies as well as CalCars demonstration vehicles show EV fuel economy closer to 3.85 miles per kWh (0.26 kWh / mile). This in turn could be balanced out by the fact that night time electricity in the UK anyway costs closer to $0.07. UK annual driving distances are also actually about 8,400 miles.

The key conclusions from this analysis are:

1) A smaller 5 kWh battery is sufficient for most drivers. They will still drive in EV mode over 50% of the time, based on average European driving distances. This smaller battery specification represents very significant upfront cost savings.

2) Use of bi-polar lead acid batteries (combined with ultracapacitors) represent cost savings of 45% even against future target prices for lithium ion batteries. When liquid cooling and battery management systems are factored in, the weight and volume of bi-polar lead acid batteries are far more competitive than is commonly perceived.

3) A Libralato engine generator allows reduced engine costs and increased fuel economy of approximately 30% when the engine is required. Due to the Libralato engine’s exceptional efficiency and near constant optimum performance, even at 70-80 mph over long distances, the engine-generator will compensate for the electrical losses of a series hybrid powertrain and will achieve about 65mpg (gasoline version; UK gallons). Over the EU driving cycle a segment C-D vehicle would achieve over 100mpg, with CO₂ emissions below 65g/km. The flexible geometry of the Libralato engine is easily adaptable to maximise performance with biofuels (both ethanol and bio-diesel). Prototypes of the Libralato engine will use digital engine management combined with lambda sensors to implement ‘flex fuel’ capability. The substantial size and weight savings afforded by the Libralato engine allow for more of the hybrid powertrain components to be located within standard engine cavities, thereby requiring little or no body work redesign. In addition to the qualities above, the low emissions, low noise and low vibration of the Libralato engine make it ideal for use as a discrete PHEV generator.

As described by Dr Kendall, author of “Plugged In: The End of the Oil Age” WWF, 2008,

“The potential for grid-connected vehicles to decimate our demand for liquid hydrocarbon fuels should be clear. Freed from the psychological barriers which hinder widespread market acceptance of pure battery electric vehicles, plug-in hybrids with an all-electric capability of just fifty kilometres would slash liquid fuel consumption, since such a high proportion of journeys undertaken are well within this range. Beyond 50 km, a significant share of the ‘residual’ liquid demand may be met with next generation biofuels. ….

Automotive transport is ripe for transformation. We need to accelerate the commercialisation of vehicles with diversified primary energy sources, high efficiency and compatibility with a sustainable, renewable energy future. The electrification of automotive transport offers a promising way to achieve this objective. Grid-connected vehicle technology – enabling all or part of every journey to be powered by electricity taken from the grid – is available based on existing infrastructure and current technology. Battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) – supplemented by sustainable biofuels for range extension – can dramatically reduce the crude oil dependency of automotive transport in an efficient and sustainable manner.”

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6 Target set by USABC, US Automotive Battery Consortium
7 Source: DfT