**New Automotive Powertrains and Fuels** **Gordon Taylor** **2003-10-20**

Summary

To meet the challenges of regulated emissions**,** oil and gas depletion, and carbon dioxide emissions, new powertrains and fuels are required for automotive vehicles. Having long been the leader in setting emission performance requirements, California has sought to mandate some Zero Emission Vehicles, such as Battery Electric Vehicles and Fuel Cell Vehicles. This paper examines how these compare with Conventional Vehicles and Hybrid Electric Vehicles, and their suitability for wider deployment and fuelling from renewable energy sources, for sustainability.

Based on consistent measured data, there is no case for deploying Battery Electric Vehicles and a greatly increased electrical infrastructure, or Fuel Cell Vehicles and a hydrogen infrastructure. Mandating Battery Electric Vehicles and Fuel Cell Vehicles would incur excessive costs for both the new vehicles and the new fuelling infrastructure. These could jeopardise many of the manufacturers, and also the meeting of the California emission performance requirements. Moreover, upgrading an electricity sector much enlarged for Battery Electric Vehicles or Fuel Cell Vehicles to renewable sources, such as hydro and wind, would also be very costly and ultimately impractical. The plant is capital intensive, and thus more expensive than e.g. fossil plant, and even renewable resources have a limited annual potential.

However, Conventional Vehicles and Hybrid Electric Vehicles can already meet and better the ULEV and SULEV standards, and thus the California fleet average emission requirements for 2010 and beyond. Furthermore, California is already using 10% bio-ethanol as an oxygenate in gasoline. Hence the petroleum usage and carbon dioxide reduction objectives could also be met with increasing proportions of bio-ethanol fuel - and without any major changes to the fuel infrastructure.

Glossary

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| ADL | Arthur D. Little Inc. A U.S. company that (until recently) carried out R & D. |
| ANL | Argonne National Laboratory - a Government Laboratory in the U.S. |
| AT-PZEV | Advanced Technology PZEV - a California classification which includes PZEV. |
| bbl | Barrel - a measure of volume, usually of petroleum or products made therefrom. Equal to 42 US gallons, 35 UK (or Imperial) gallons, 159 litres, or 0.159 cubic meters. |
| BEV | Battery Electric Vehicle |
| BTU | British Thermal Unit - a unit of energy, equal to 1055 Joules. |
| CAFE | Corporate Average Fuel Economy - a U.S. Federal requirement, with different values for passenger cars (27.5 mpg) and for SUVs and light trucks (20.7 mpg). |
| CARB | California Air Resources Board. |
| Carnot | An ideal thermodynamic cycle for converting heat (from combustion of a fuel) to work. |
| CO | Carbon Monoxide - a type of regulated automotive emission. |
| $CO_2$ | Carbon Dioxide - a type of automotive emission (not regulated as such, but only via fuel economy requirements). It is also the most important Greenhouse Gas (after water). |
| CV | Conventional Vehicle - fuelled by gasoline, with an ICE (without hybrid features). |
| CVT | Continuously Variable Transmission - one which is stepless (between certain limits). It may be realised with a belt between two conical pulleys, or with two electrical machines. |
| DC | DaimlerChrysler - a German automobile manufacturer with a large presence in the U.S. |
| DOD | Depth of Discharge of a battery. Equal to 1 - State of Charge (SOC). |
| E10 | A blend of 10% ethanol and 90% gasoline. Available in the U.S. and Sweden. |
| E23 | A blend of 23% ethanol and 77% gasoline. Available in Brazil. |
| E85 | A blend of 85% ethanol and 15% gasoline. Available in the U.S. and Sweden. |
| E100 | A fuel of 100% ethanol (with denaturants to discourage drinking). Available in Brazil. |
| EPA | An agency of the U.S. Government. |
| E.U. | European Union |
| EUDC | (E.U.) Extra-Urban Driving Cycle, used for determining automotive emissions and fuel economy. |
| FCHV | Fuel Cell Hybrid Vehicle. Also used by Toyota to describe their FCHV prototypes. |
| FC | Fuel Cell (usually a stack of such), using hydrogen and oxygen to produce electricity. |
| FCV | Fuel Cell Vehicle, without or with hybrid features. |
| FFV | Flexible Fuel Vehicle - usually one which can use gasoline, E85, and any mixture thereof. |
| FTP | (U.S.) Federal Test Procedure - a driving cycle used for determining automotive emissions and fuel economy. It comprises City and Highway segments. |
| Gallon | A unit of volume usually applied to liquids, such as fuels. 1 U.S. gallon = 3.785 litres and 1 U.K. gallon = 4.546 litres. |
| Gasoline | Fuel used in spark-ignition ICEs. Otherwise known as petrol. |
| GM | General Motors Corporation - a U.S. automobile manufacturer. |
| HCHO | Formaldehyde - a type of regulated automotive emission. |
| HEV | Hybrid Electric Vehicle. See 'Parallel' and 'Series'. |
| HHV | Higher Heat Value - the calorific value of a fuel including the latent heat of vaporisation of any water produced. Also known as the Gross Calorific Value. |
| HSD | (Toyota) Hybrid Synergy Drive, otherwise known as THS II. |
| HV | Hybrid Vehicle - one with a prime mover (usually an ICE or FC) and an energy store. |
| ICE | Internal Combustion Engine - usually a piston engine running on gasoline or other fuel. |
| J | Joule - a unit of energy. |
| kW | KiloWatt - a unit of power equal to 1000 Watts. |
| kWh | KiloWatt-hour - a unit of energy equal to 3600 Joules. |
| LDVs | Light Duty Vehicle - i.e. passenger cars, SUVs and light trucks. |
| LEV | Low Emission Vehicle - a California standard for automotive emissions. |
| LHV | Lower Heat Value - the calorific value of a fuel excluding the latent heat of vaporisation of any water produced. Also known as the Net Calorific Value. |
| MIT | Massachusetts Institute of Technology - a university in the U.S. |
| mpg | Miles per gallon. In this paper, the U.S. gallon is assumed unless stated otherwise. |

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| mpg ge | Miles per gallon gasoline equivalent. This is a measure of fuel economy per unit of fuel divided by the ratio of the LHV of the actual fuel (e.g. hydrogen) to that of gasoline. The LHV of 1 kg of hydrogen is very close to that of 1 U.S. gallon of gasoline. |
| MTBE | Methyl Tertiary Butyl Ester - an oxygenate for gasoline, intended to reduce emissions. |
| Mtoe | Million tonnes oil equivalent - a measure of energy equal to 11.63 TWh = 41.87 PetaJoules |
| MY | Model Year. Automobiles are typically put on sale before the start of the calendar year. |
| NECAR | A series of fuel cell vehicle prototypes produced by DaimlerChrysler. |
| NEV | Net Energy Value - the ratio of energy in a fuel to the (non-renewable) energy required to produce it. |
| NiMH | Nickel Metal Hydride - a high performance battery often used in BEVs and HEVs. |
| NMOG | Non-Methane Organic Gases - a type of regulated automotive emission. |
| NOx | Nitrogen Oxides - a type of regulated automotive emission. |
| NREL | National Renewable Energy Laboratory - a Government Laboratory in the U.S. |
| OBD II | On-Board Diagnosis equipment for monitoring the emission controls equipment. |
| ORNL | Oak Ridge National Laboratory - a Government Laboratory in the U.S. |
| Parallel | A type of hybrid powertrain made up of a prime mover (often an ICE), one or two electrical machines, usually of lower power, and a storage device, such as a battery or super-capacitor. |
| PEM | Proton Exchange Membrane - the type of fuel cell usually considered for automobiles. |
| PGM | Platinum Group Metals - Platinum, Palladium, and Rhodium - scarce and expensive metals often used in automotive catalysts and in fuel cells. |
| PHEV | Plug-in Hybrid Electric Vehicle. This is a combination of an HEV with a BEV. |
| PM | Particulate Matter - a type of regulated automotive emission. A particular problem with Diesel engines. |
| PNGV | Partnership for a New Generation of Vehicles. A program involving several U.S. Government Laboratories (funded partly by the U.S. Government), and the U.S. automobile industry. The headline target was a fuel economy of 80 mpg, and the resulting rolling prototypes were all HEVs with small (1.1 to 1.5 l) Diesel engines, electric motors and small batteries. |
| PZEV | Partial Zero Emission Vehicle - a California classification which includes SULEV. |
| R & D | Research and Development. |
| RFG | Reformulated Gasoline - as used in California to reduce emissions. |
| Ricardo | A British company specialising in R & D on powertrains and fuels. |
| SC03 | (U.S.) driving cycle for determining automotive emissions with and without A/C in operation. |
| Series | A type of hybrid powertrain made up of a prime mover (either an ICE or a FC), two electrical machines of about the same power, and a storage device, such as a battery or super-capacitor. |
| SFTP | (U.S.) Supplemental Federal Test Procedure, comprised of SC03 and US06. |
| SOC | State of Charge of a battery. Equal to 1 - Depth Of Discharge (DOD). |
| SOx | Sulfur Oxides - a type of (unregulated) automotive emission. |
| SULEV | Super Ultra Low Emission Vehicle - a California standard for automotive emissions. |
| SUV | Sports Utility Vehicle - one with a high-built, off-road style, often with four-wheel drive. They are treated not as passenger cars, but as light trucks for the U.S. Federal CAFE fuel economy requirements. |
| THC | Total HydroCarbons - a type of regulated automotive emission. |
| THS | Toyota Hybrid System - a patented series-parallel hybrid drivetrain. |
| THS I | The THS used in the 1998 (Japanese) and 2001 (overseas) model Prius HEV. |
| THS II | The THS used in the 2004 model Prius HEV. Otherwise known as the HSD. |
| TLEV | Transition Low Emission Vehicle - a California standard for automotive emissions. |
| UDC | (E.U.) Urban Driving Cycle, used for determining automotive emissions and fuel economy. |
| ULEV | Ultra Low Emission Vehicle - a California standard for automotive emissions. |
| U.S. | United States of America. |
| US06 | (U.S.) driving cycle for determining automotive emissions under high speeds and loads. |
| W | Watt - a unit of power equal to 1 Joule per second. |
| ZEV | Zero Emission Vehicle (at the point of use). These include BEVs and FCVs. |

## 1) Introduction

To meet the challenges of regulated emissions, oil and gas depletion, and carbon dioxide emissions, new powertrains and fuels are required for automotive vehicles. This paper considers passenger cars and light trucks, rather than heavy trucks and buses. Legislators in California - advised by the Air Resources Board - have sought to mandate 'Zero Emission Vehicles', such as Battery Electric Vehicles and Fuel Cell Vehicles. While California may wish to lead, there are also implications for the wider world. Hence it is essential to consider the science, the realities of engineering, and the costs and benefits of each option. With about half the world resources of oil and gas already consumed, the era of cheap fuel is over.[1] One obvious response is to make and use vehicles that are far more energy efficient. Lower rolling and aerodynamic resistances and lighter weight structures are equally applicable to vehicles with all types of powertrains - including conventional. However, they are not considered in this paper.

For regulated emissions, oil and gas usage, and carbon dioxide emissions to be greatly reduced - and to increase sustainability - any valid option would need to be widely replicated across the light vehicle fleets world-wide and fuelled from renewable energy sources. However, the cost of various combinations of vehicle powertrains and fuels could be very high - particularly if both the vehicles and the fuel infrastructure had to be replaced. The latter could become particularly costly when the fuel was produced from renewable sources, as would be required for sustainability. Hence this paper examines the publicly available measured data to determine the regulated emissions and energy efficiency for various combinations of vehicle fuels and powertrains, and thus whether they offer commensurate - or indeed any - advantages.

## 2) Objectives

### a) Regulated Emissions

Automotive powertrains are subject to large and rapid changes in loads, which affect their emissions. Hence these are determined under prescribed conditions, usually specified as driving cycles. The main driving cycles considered here are the US FTP-75, the EU UDC and EUDC, and the Japanese 10-15 mode and 11 mode cycles. However, there are also Australian and Chinese driving cycles.

In the various jurisdictions, differing requirements apply - and from different dates. The usual regulated emissions are Total HydroCarbons (THC), Carbon Monoxide (CO), and Nitrogen Oxides (NOx). In California, hydrocarbons are specified as Non-Methane Organic Gases (NMOG) and Formaldehyde (HCHO). There are also limits on Particulate Matter (PM) for diesel engine vehicles. In practice, the California SULEV standard is usually regarded as the most demanding. For the rest of the USA, different requirements apply, but are not considered here. However for other markets, certification to their own standards is still required. The principal requirements are given in the following table: [2]

| Regulated Emission Standards | | | | | | |
|---|---|---|---|---|---|---|
| 1) US California | Standard | NMOG | CO | NOx | HCHO | Measure & Cycle |
| From MY 1994 | TLEV at 50,000 miles | 0.125 | 3.4 | 0.4 | 0.015 | g/mile FTP |
| | LEV at 50,000 miles | 0.075 | 3.4 | 0.2 | 0.015 | |
| As at MY 2001 | ULEV at 50,000 miles | 0.040 | 1.7 | 0.2 | 0.008 | |
| | ULEV at 100,000 miles | 0.055 | 2.1 | 0.3 | 0.011 | |
| From MY 2004 | SULEV at 120,000 miles | 0.010 | 1.0 | 0.02 | 0.004 | |
| 2) Europe | | THC | CO | NOx | | |
| As at MY 2001 | Step 3 at 80,000 km | 0.20 | 2.3 | 0.15 | | g/km UDC+EUDC |
| From 2005.1 | Step 4 at 100,000 km | 0.10 | 1.0 | 0.08 | | |
| 3) Japan | | THC | CO | NOx | | |
| As at MY 2001 | H12 stds. at 80,000 km | 0.08 | 0.67 | 0.08 | | g/km 10-15 mode |
| | | 2.2 | 1.90 | 1.4 | | g/test 11 mode |
| Guideline | J-ULEV at 80,000 km | 0.02 | 0.67 | 0.02 | | g/km 10-15 mode |
| | | 0.55 | 1.90 | 0.35 | | g/test 11 mode |

Effects of Cooling the Interior and of Hard Driving

Effective cooling of the interior is required for vehicles to be operated safely and sold widely. This can require an additional load of several kW - and at all speeds. [3] For Battery Electric Vehicles (BEVs), and Plug-in Hybrid Electric Vehicles (PHEVs) in BEV mode, the load due to interior cooling may significantly reduce the driving range. For Conventional Vehicles (CVs) - or potentially any type of vehicle - 'emission increases with air conditioner usage have been undercounted'. [4] In the USA, the SC03 test is now used for measuring emissions without and with air conditioning on maximum, with a specified ambient temperature and solar load.

CARB became concerned that the Federal Test Procedure (FTP) did not sufficiently 'capture' the regulated emissions under high speeds and loads. After working with the US EPA and other interested parties, the US06 driving cycle was adopted. [5]

In California and the wider USA, the effects of both air conditioning operation and of aggressive driving on emissions are now monitored by the Supplemental Federal Test Procedure (SFTP). This consists of the SC03 and US06 driving cycles, and the emission results are added to those of the FTP, with the weightings FTP 35%, SC03 37%, and US06 28%. They are subject to the same limits as before. [6]

Testing

Testing against the California emission requirements is done with Reformulated Gasoline (RFG). This has a sulphur content of only 30 ppm - both to reduce Sulphur Oxide (SOx) emissions, and to allow catalytic emission controls to be more effective for other emissions. Elsewhere in the USA, it is about 300 ppm, but - for the same reasons - will be reduced to an average of 30 ppm by 2007. [7]

Due to the importance of transient speeds and loads, until recently emissions could only be measured on real vehicles - or at least engines on a suitable dynamometer. However, simulation techniques are being developed which show promise of useful accuracy. [8]

California also has requirements for evaporative emissions - mostly from the fuel system. While they are precursors of smog, with a controlled system the contribution is small, and they are not considered here.

In California, under the 'LEV' program, which ran up to 2003, the various models from a given manufacturer could be certified to differing emission standards - TLEV, LEV, ULEV, and SULEV. Regarding the SULEV standard, 'emissions from vehicles in this category are close to emissions from powerplants associated with recharging electric vehicles'. [9] However, the crucial performance requirement was a fleet average emissions per vehicle (weighted for sales in California) - expressed as NMOG - which declined progressively.

The California ZEV proposals

Under the 'LEV II' program, the fleet average requirement is due to decline further, from NMOG of 0.053 g/mile for 2004 to 0.035 g/mile for 2010 and subsequently. In addition, California is seeking to 'mandate' or oblige the large-volume manufacturers to certify a certain percentage of their sales as Zero Emission Vehicles (ZEVs). These are BEVs, Fuel Cell Vehicles (FCVs), and possibly PHEVs capable of operating in BEV mode, and have near-zero regulated emissions attributed to them.[10] One study estimated the effect of the California ZEV Mandate (as then proposed) as 500,000 BEVs and 500,000 FCVs by 2020. [11] With the car fleet estimated to be 8.6 million and the light truck fleet to be 3.9 million in 2020, even assuming that the ZEVs were responsible for no regulated emissions, the reduction by 2020 might be only 8%.

In the latest CARB proposal of April 2003, for the six high-volume manufacturers, 6% must be PZEVs, and 2% AT-PZEVs. In addition, 'Gold' ZEVs (BEVs and FCVs) must be 2% of sales in 2005 and 5% of sales in 2018 - of which at least 50% must be FCVs. [12] These could accumulate to about 166,500 - i.e. about 1.3% of the California light vehicle fleet by 2020. Alternatively, the manufacturers may choose 6% PZEVs, 4% AT-PZEVs, and their sales-weighted share of approximately 250 FCVs - of which up to half may be substituted by BEVs - by 2008, and more later. However, while adopted by the Board (CARB), this prescriptive requirement has been resisted by the manufacturers through legal challenges, resulting in delay. [13]

**b) Petroleum Use and Carbon Dioxide Emissions**

California has a petroleum reduction policy - in part because of the consequences of oil spills on water and on land. [14] In addition, it has a policy to reduce carbon dioxide emissions, intended to limit the local effects of global warming, and expressed in a law AB 1493. [15] California has already set the precedent of its own clean fuel - RFG - with a lower sulphur content than elsewhere in the USA. It has also required the oil companies to phase out Methyl Tertiary Butyl Ether (MTBE) as a gasoline oxygenate and replace it with ethanol at 10%. This is far safer - being less poisonous and bio-degradable in the event of spillage. Even at the 10% level, the use of bio-ethanol will help to reduce petroleum use and carbon dioxide emissions.

**3) New Powertrains and Fuels**

The Powertrain Options

A powertrain that includes a short term storage device, such as a flywheel or battery, together with a suitable transmission or motor-generator, is known as a hybrid. This can shield the Internal Combustion Engine (ICE) or Fuel Cell (FC) from transients, recover energy during decelerations, and provide additional power during accelerations. Thus hybridisation can give considerable reductions in regulated emissions and in fuel consumption. Hence, as replacements for Conventional ICE Vehicles (CVs), the powertrain options considered are ICE Hybrid Electric Vehicles (HEVs), BEVs, PHEVs, and FCHVs.

The HEVs considered in this paper are 'full' (as opposed to 'mild') hybrid vehicles, with high power, high voltage motors - Type III in CARB parlance. [16] Full hybrids give the best improvement in regulated emissions and fuel economy, and any additional cost is small compared with those of BEVs and especially of FCVs.

The BEVs considered are so-called 'full function' BEVs, with 4 to 5 seats, and a range of roughly 100 miles. [17] For the present purpose, a PHEV may be considered as a combination of an HEV, capable of being refuelled, and a BEV with an electric range - e.g. 20 miles.

FCVs are refuellable (like CVs and HEVs), rather than re-chargeable (like BEVs and PHEVs). However, for FCVs the electric motor is full size (as in series HEVs, BEVs and PHEVs), not just part size (as in parallel or series-parallel HEVs). The Fuel Cell Vehicles considered here are hybrids - i.e. they have a traction battery to de-couple the instantaneous power of the fuel cell from that required for propulsion. By using the battery to help meet peak power demands, it allows the fuel cell stack to be smaller. Also, the drive-away time can be shortened and the drivability (transient response) improved. In addition, it enables regenerative braking, which reduces the net energy consumption over a driving cycle. Most prototype FCVs are now hybrids (FCHVs), including those of DaimlerChrysler (DC), Ford, Honda, and Toyota. Only those of General Motors (GM)/Opel are not. Ford said that hybridising their FCV gave about a 25% improvement in overall 'fuel economy'. [18] Also Toyota have reported that hybridising increased the tank-to-wheel efficiency from 38 to 50%, and thus the well-to-wheel efficiency from 22 to 29% - i.e. by 32%.[19]

The Fuel Options

CVs and HEVs can use gasoline and ethanol, both of which have the medium energy quality or 'exergy' typical of conventional fuels. (Diesel fuel is not considered in this paper, since it is not popular in some territories - including California and the USA generally - due to high emissions of particulates). Conversely, BEVs and PHEVs and the hydrogen-fuelled FCHVs considered here all involve the use of electricity, which has the highest exergy of any commercial energy form. On a simple energy accounting view, this might not seem important. However, on a thermodynamic view, the energy form with the lower exergy would be preferable because higher energy quality always has to be paid for. The conversion of fuels to electricity always involves appreciable losses - due either to Carnot limitations and other losses in thermal power stations, or to electro-chemical limitations and other losses in fuel cells. These - and the cost of the associated capital plant - are reflected in the price of the energy.

Moreover electricity is hard to store. In stationary plant, it may be stored as potential energy, such as pumped storage - a hydroelectric plant with provision for re-charging by pumping the water back uphill. In mobile plant, some have proposed storage as potential energy (using hydraulics to compress a gas spring) or as kinetic energy - in a flywheel, which may be charged and discharged via an electrical machine (motor/generator). However, for road vehicles, the two main methods used are storage in a battery, or as a synthetic fuel, such as hydrogen, which is then converted in a fuel cell stack.

The Powertrain and Fuel Combinations

The combinations considered initially in this paper are BEVs and PHEVs in BEV mode with electricity, FCHVs with hydrogen, and CVs, HEVs, and PHEVs in HEV mode with gasoline. With renewable fuel sources, the combinations considered are BEVs and PHEVs in BEV mode with electricity, FCHVs with hydrogen, and CVs, HEVs, and PHEVs in HEV mode with increasing amounts of bio-ethanol. In practice, with spark-ignition (gasoline-type) engines, ethanol can be used as an oxygenate at about 10%, and up to about 23% in standard engines. Where ethanol is widely available, as in Brazil, it can be used at 100% in dedicated engines. However in the USA and elsewhere, E85 - a blend of 85% ethanol with 15% gasoline, to improve cold starting - is usually used in Fuel Flexible Vehicles (FFVs). These have a sensor in the fuel line, which controls the engine fuel flow and ignition to allow the use of E85, 100% gasoline, or any mixture of the two, drawn from a single tank. Several vehicle models - with engines of around 3 litres - are available as FFVs from some of the major manufacturers. Such vehicles are sold in the USA at no additional cost, and some two million have been sold to date. [20] The Ford Focus is available as a FFV in Sweden, and a few thousand have been sold. [21]

Ethanol is a liquid at normal temperatures and pressures, and very easy to store and transfer. It has a Lower Heat Value (LHV) per unit volume 2.3 times that of liquid hydrogen and 66% of that of gasoline. When blended as E85, the range from a given fuel tank is typically 72% of that on gasoline. [22] Moreover, E85 could meet the CARB requirements for low fuel cycle emissions - i.e. a marginal NMOG of not more than 0.010 g/mile. [23] The marginal NMOG for E85 is 0.310 g/gallon. [24] Therefore the CARB requirement would be met at a vehicle fuel economy of 31 mpg or more. Such fuel economies are easily achieved with CVs - and especially with HEVs.

**a) Regulated Emissions**

The California fleet average emissions requirements could be met (as in the earlier LEV program) with a mix of models certified as TLEV, LEV, ULEV, and SULEV. Already several CVs have demonstrated their ability to meet the SULEV standard. Indeed, several CVs have even achieved the PZEV standard, with SULEV regulated emissions, near-zero evaporative emissions, and a 150,000-mile warranty on the emission controls. [25] Since such vehicles are equipped with OBD II for monitoring, this should mean that emissions over the vehicle lifetime are no longer an issue. [26]

HEVs allow the instantaneous power produced by the engine to be de-coupled from that required for vehicle propulsion (plus accessories) - with the battery and motor providing any difference. This has a marked effect in reducing the transients imposed on the engine - and thus on emissions. Daimler-Benz reported in 1997 that their C-class series hybrid prototype vehicle could achieve very low emissions. For the US FTP-75 driving cycle, NMOG was 0.003, CO was 0.115, and NOx was 0.011 g/mile. [27] These are 70%, 88%, and 45% below the California SULEV limits.

Toyota launched the Prius full hybrid production vehicle - initially for the Japanese market - in 1997. A modified version for North America and Europe was put on sale in 2000. The Toyota Hybrid System (THS) allows the engine to be operated so as to warm up the catalysts as quickly as possible, and not to cool them unduly during the many engine-off periods. With drive by wire, and a powerful electric motor, the engine is also shielded from sharp transients that would otherwise cause increased emissions. After 120,000 miles on CARB Phase II gasoline, the 2001 Model Year (MY) Toyota Prius achieved emissions of NMOG 0.0034, CO 0.34, NOx 0.008, and HCHO zero g/mile. [28] These are 66%, 66%,and 60% below the SULEV limits, and it was certified as meeting the SULEV standard. Other features that are designed to control evaporative emissions enabled this vehicle to achieve the California PZEV rating. [29] Moreover, the 2004 Toyota Prius is expected to achieve the AT-PZEV rating, with 0.7 PZEV credits. [30] Furthermore, the regulated emissions have been reported as 30% below those of the 2003 Prius, making it the cleanest car on the planet. [31] This would imply that they are about 100 - (100-60)*(100-30) = 72% below the SULEV limits.

**b) Petroleum Use and Carbon Dioxide Emissions**

Well-to-Tank Efficiency

Petroleum use and carbon dioxide emissions are functions of the so-called 'well-to-wheel' efficiency. This is usually considered in two stages - well-to-tank efficiency for the upstream fuel cycle, and tank-to-wheel efficiency for the vehicle over a driving cycle.

Special care is necessary when interpreting data for powertrains using hydrogen - for which the difference between the Lower Heat Value (LHV) and Higher Heat Value (HHV) (due to the latent heat of vaporisation of the water produced) is particularly large. The tank-to-wheel efficiency is almost always quoted on the LHV basis, yet the upstream processes must invest the full HHV. Hence the well-to-tank efficiency must be expressed as the LHV output over the HHV input in order to obtain the correct value for the well-to-wheel efficiency. Thus the safest method is to express all such data on the HHV basis. However, in this paper, the original values - quoted on the LHV basis - have been retained.

The well-to-tank efficiency is relatively easy to determine, since it depends only on the technology used to produce and distribute the fuel, and is independent of any vehicle characteristics or the driving cycle. However, often many pathways are possible, so this should also be identified when quoting well-to-tank efficiencies. The extensive data is usually handled by a computer program, such as GREET from ANL. [32]

Oil and gas usage and carbon dioxide emissions depend on the fuel used and its carbon intensity. For example, the carbon intensity of natural gas is less than that of gasoline. However, it is needed for many other purposes - e.g. making chemicals, electricity generation, and building heating and cooling. Moreover, the world production is approaching its peak, and will soon start to decline. [33] Hence using natural gas - even to make hydrogen - could only ever be a short term option.

Even when considering fuel produced from renewable sources, the well-to-tank efficiencies are important. This is because there may still be significant fossil energy inputs to the production of the fuel. The fuel cycle energy (on a BTU/mile basis) of ethanol from California biomass or waste paper is about 20% of that of gasoline, while that of ethanol from corn is about 50%, implying a Net Energy Value (NEV) of 1.50. [34] Another reference gives the NEV of ethanol from corn as 1.34, but much of the fossil energy input is US gas and coal, so the petroleum saving ratio is 6.34:1. [35] Moreover, these ratios should continue to improve - both with corn and with other feedstocks. [36]

Hence wider use of ethanol blends could reduce petroleum use and carbon dioxide emissions - and at a very fast rate, without waiting for vehicles to be replaced. Moreover, unlike California's earlier attempt to reduce carbon dioxide emissions by setting fuel economy standards, this is less likely to be vetoed by the Federal Government, since to do so would involve opposing decreasing petroleum imports and increasing US farm incomes.

California could increase the use of bio-ethanol beyond 10% as an oxygenate - up to 23% ethanol (as in Brazil) for CVs and HEVs, and E85 for FFVs - again both CVs and HEVs. The vehicle manufacturers have been granted a major concession on the US Federal CAFE fuel economy targets in respect of every FFV that they sell - on the assumption that they would use E85 50 per cent of the time. However, they actually run on gasoline 99 per cent of the time. [37] Therefore to encourage the use of E85, taxes should be adjusted to make it consistently cheaper than gasoline - not on a volume basis but on an energy basis.

Tank-to-Wheel Efficiency

Where the fuel is fixed - e.g. gasoline - petroleum use and carbon dioxide emissions depend only on the tank-to-wheel conversion efficiency. This depends on both the vehicle characteristics and the driving cycle considered. The main driving cycles considered here are the US FTP-75, the EU UDC and EUDC, and the Japanese 10-15 mode and 11 mode cycles. (In the USA, the SC03 and US06 cycles are not considered when calculating fuel economy). The tank-to-wheel efficiency is usually determined by measurement on real vehicles, or at least engines on a suitable dynamometer. However, it can also be calculated quite accurately by simulation programs, such as Advisor from NREL or P-SAT from ANL. [38]

CVs, HEVs and PHEVs in HEV mode

All transport involves the overcoming of resistances to motion, which is known as work (mechanical energy). The conversion of heat (thermal energy) to work is known as thermodynamics. For heat engines, such as internal combustion engines (ICEs), the efficiency of conversion is limited to that of the Carnot cycle. This is (T1-T2)/T1, where T1 is the top (or flame) temperature, and T2 is the bottom (or ambient) temperature - both expressed as absolute temperatures. With a flame temperature of 1827 C (i.e. 2100 K), and an ambient temperature of 20 C (i.e. 293 K), the Carnot cycle efficiency would be 86 %. However, this is an ideal cycle, and due to various losses, real automotive engines achieve only a fraction of this - less than half at best - and the efficiency also varies with load. (Modern thermal power stations are around 1000 times as large, and much more complex, and can achieve up to about two-thirds of the Carnot efficiency).

'Full' HEVs may save fuel in several ways: a down-sized Atkinson-cycle engine, designed for best efficiency, rather than for power, supplemented as required by a powerful electric motor and battery. Idle-stop and electric operation at low speeds and loads, where engine operation would be inefficient. A Continuously Variable Transmission (CVT), which displaces the engine operating point from the road load line to the best efficiency line. A powerful electric generator and battery able to recover some of the energy normally lost on braking (regenerative braking). Compared with a CV of the same weight, the Toyota Hybrid System (THS) in the 2001 Toyota Prius HEV enables the average engine thermal efficiency over a driving cycle to be about doubled, and hence the fuel consumption to be about halved. [39]

BEVs and PHEVs in BEV mode

Work can also be done by electric motors, drawing their energy from storage batteries. However, all batteries have a fundamental disadvantage - they have to carry their oxidant as well as their fuel. (Conversely, both internal combustion engines and fuel cells use oxygen from the air). Therefore batteries are bound to be heavy, and increase the energy consumption of the vehicles concerned. However, the weight is more or less proportional to the energy stored. The batteries of HEVs and FCHVs are small, with energy storage capacities of about 1 or 2 kWh. In contrast, those of BEVs and PHEVs are much larger - of about 6 kWh for PHEVs with an electric range of say 20 miles, and about 30 kWh for BEVs with a range of about 100 miles.

For BEVs and PHEVs, the greater battery weights also necessitate more powerful motors for equal acceleration performance. Instead, as BEVs, both the Honda EV Plus and the Toyota RAV4 EV offer acceleration from 0 to 60 mph in about 18 s. [40] This is much slower than that for the 2001 Toyota Prius HEV at about 12.5 s. ANL have shown - for both CVs and HEVs - that fuel economy should be compared at equal performance. [41]

A PHEV battery suffers from conflicting requirements. An HEV battery is designed for high specific power, and to cycle not very deeply but very many times a day, yet last the life of the vehicle. Conversely, a BEV battery is designed for high specific energy, and to be cycled deeply but typically only once per day. An ANL study found that for a PHEV the battery could have only compromise values for specific power and specific energy - so the result would be inferior in both HEV and BEV modes. [42] For PHEVs, to minimise the battery weight and cost, the electric range in BEV mode is usually only achieved at lower speeds - e.g. those permitted in urban areas - as opposed to those highway speeds that the vehicle can achieve in HEV mode. [43]

FCHVs

Work can also be done by electric motors, with the electricity generated by fuel cells. Although they are not subject to thermodynamic (Carnot cycle) limits, the efficiency of conversion of chemical energy to electric energy is still limited. In the case of the hydrogen-oxygen electro-chemical pair, this maximum efficiency is some 83 per cent. However, this too is an ideal, and real fuel cell systems achieve only a fraction of this - e.g. a half at best - again due to various losses, and the efficiency also varies with load.

For a FCHV, even with direct hydrogen fuelling, the fuel cell stack may take time - e.g. several minutes - to reach full power, yet there are relatively large parasitic loads (for pumps and fans), and users expect to drive away promptly. Hence the battery may need to be somewhat bigger than that of a HEV.

Again for FCHVs, high performance is expensive. 'Fuel cell vehicles most likely will have reduced top speeds and acceleration rates in comparison to IC engine vehicles to reduce vehicle costs. In addition, it is likely that they will be heavier and have reduced trunk storage space'. [44]

Effects of Climatic Extremes

Starting and running the powertrain.

Batteries are adversely affected by low temperatures. This was probably one reason why the GM EV1 and the Toyota RAV4 EV BEVs were offered only in California and Arizona. All FCVs use hydrogen in the fuel cells, hence produce water, and are prone to freezing up at low temperatures. This can be overcome, but involves very considerable engineering development. [45] Fuel cell stacks also have very large cooling loads to be rejected to the atmosphere - largely because the exhaust losses are very low. Compared with those of internal combustion engines, the size, weight, and cost of fuel cell cooling systems are much larger. For example, the radiator could be 24 in high and 48 in wide (i.e. 0.6 x 1.2 m). [46] The fan power consumption and the aerodynamic drag due to the cooling airflow are also likely to be much higher.

Heating the interior

Effective heating of the interior (and clearance of the windshield etc.) is required for vehicles to be operated safely and sold widely. This can require an additional load of several kW - and at all speeds. [47] For BEVs, and PHEVs in BEV mode, the load due to interior heating may significantly reduce the range. One option would be to use electric resistance heating, but the accessory load could be reduced - at some cost in complication - by using a heat pump for interior heating. (The air conditioner is designed to allow it to be used for heating, as well as for cooling). The GM EV1 BEV used, and the Toyota FCHV uses, heat pump heating. Some BEVs - e.g. the GM Chevrolet S-10 and Ford Ranger EV pickups - have even adopted fuel-fired heaters. These then require testing for emissions. Conversely, HEVs have the advantage of usually having enough engine reject heat for interior heating, so no accessory power need be expended, and the performance and range are not affected.

Moreover, as average traffic speeds fall due to congestion, the effect of such accessory loads will weigh ever more heavily, since heating and cooling energy demands depend primarily on time, while propulsion energy demands depend mainly on distance and speed. If BEVs or FCVs were to be widely adopted, a test similar to SC03, but carried out at say 0 C, or even lower, might be needed to determine the impact of interior heating on range.

Overall Well-to-wheel Efficiency

For BEVs, very little data measured on actual vehicles has been found. However, the well-to-wheel efficiency may be estimated as:

Coal mine to power plant, say 98%
Power plant to electricity, say 36.2% (HHV basis) [48]
Electricity to home, say 93%
Home charger to car traction battery, say 85% [49]
Well-to-tank efficiency, say 31%

Traction battery charge-discharge to motor, say 90% [50]
Motor to wheel (average), say 77% [51]
Tank-to-wheel efficiency, say 69.3%

Well-to-wheel efficiency, say 21.5%.

On the Southern California Edison mix of fuels, the fuel cycle energy of a BEV is about 4000 BTU/mile. [52] The EPA results for the energy economy of the Honda EV Plus is about 2 miles/kWh and for the Toyota RAV4 EV is about 3 miles/kWh. [53] [54] Hence, depending on which the 4000 figure applies to, the well-to-wheel efficiency would be about (3412/2)/(4000 + (3412/2)) = 30% or about (3412/3)/(4000 + (3412/3)) = 22% respectively.

Greenhouse gas emissions are largely of carbon dioxide, and hence an indicator of the well-to-wheel efficiency. According to the EPA, the annual greenhouse gas emissions for the Toyota RAV4 EV BEV on the US average generation mix is 3.8 tons CO2-eq, while the 2001 Toyota Prius HEV on gasoline emits 4.0 tons CO2-eq. This is based on the full well-to-wheel greenhouse gas output for an annual mileage of 15,000, using the GREET model. Hence this HEV is only 5% worse than this BEV. However, the 2004 Prius fuel economy is about 15% higher, making the greenhouse gas emissions some 10% lower than for this BEV.

The well-to-wheel studies lead by GM used calculated values for HEVs and FCVs. (They did not consider BEVs). [55] That from MIT was similar. [56] The study from Ricardo used real measurements on a diesel mild HEV 'Imogen', and simulated the performance of FCVs. [57] All concluded that FCVs had little or no advantage over diesel HEVs.

Fortunately, for HEVs and FCVs some actual measured data (as distinct from calculated values or - particularly - targets) has been published. (a) Feng An et al at ANL were the first to analyse gasoline and diesel HEVs on the basis of measurements on more than one vehicle. [58] These were four Japanese production HEVs, two US pre-production HEVs, and three US rolling prototype diesel HEVs from the PNGV program. This analysis showed that commercial gasoline HEVs gave fuel economies about 57% higher than those of CVs. (However, this data included both 'mild' and 'full' HEVs).

In order to reduce the cost of the infrastructure, some have proposed the fuelling of FCVs with hydrogen-rich liquid fuels, such as methanol, ethanol, or gasoline. During a trip across the USA, the DC NECAR 5 FCHV covered 3262 miles in a driving time of 85 hours - i.e. at an average speed of 38.4 mph. (b) It was reported as using about twice as many gallons of methanol as a CV would of gasoline. [59] Since the ratio of the LHVs per gallon is 2.03, the tank-to-wheel efficiency of this methanol FCHV is evidently no better than that of a gasoline CV. Compared with a hydrogen FCHV, there are losses in the fuel processor/reformer, while the fuel cell output and efficiency are both lower when fed with reformate. Since the well-to-tank efficiency for methanol is lower than that for gasoline, the well-to-wheel efficiencies of methanol FCHVs would be lower than those of gasoline CVs. Yet, as it is more difficult to reform gasoline than methanol, a gasoline fuelled FCHV would probably also have a well-to-wheel efficiency lower than a gasoline CV - never mind a gasoline HEV.

(c) More recently, Toyota have published well-to-tank, tank-to-wheel, and well-to-wheel efficiencies for gasoline HEVs and hydrogen FCVs based on measurements on actual vehicles. [60]

| Efficiency | Well-to-Tank | Tank-to-Wheel | Well-to-Wheel |
|---|---|---|---|
| CVs with gasoline | 88% | 16% | 14% |
| THS I HEVs with gasoline | 88% | 30% | 26% |
| FCHVs with hydrogen made from natural gas | 58% | 50% | 29% |

Moreover, these are for vehicles of production quality, not just rolling prototypes.

For hydrogen fuelled FCHVs, an ADL study reported measured data as Fuel Economy Ratios for two such. (d) For the Ford P2000 HFC versus a P2000 gasoline vehicle, the ratio was 1.9, and (e) for the DC NECAR 4 versus an A-Class gasoline vehicle, it was 1.8. [61] However, for a well-to-wheels comparison, these values should be corrected for the different upstream losses in producing the two fuels. On the LHV basis, the well-to-tank efficiency for hydrogen produced from natural gas is about 58% and that for gasoline is about 88%, [62] so the 'upstream energy ratio' of the two fuels is 88/58 = 1.52. For the Ford and DC FCHVs compared with the corresponding CVs, the Fuel Economy Ratio / the 'upstream energy ratio' = 1.9/1.52 = 1.25 and 1.8/1.52 = 1.18. Hence the well-to-wheel efficiencies of these hydrogen FCHVs are not much higher than those of gasoline CVs - never mind gasoline HEVs.

(f) Following the first showing of the 2004 Prius, Toyota published well-to-tank, tank-to-wheel, and well-to-wheel efficiencies for a CV, a HEV, and a FCHV, based on actual measured data. [63]

| Efficiency | Well-to-Tank | Tank-to-Wheel | Well-to-Wheel |
|---|---|---|---|
| CV with gasoline | 88% | 16% | 14% |
| HSD (THS II) HEV with gasoline | 88% | 37% | 32% |
| FCHV with hydrogen made from natural gas | 58% | 50% | 29% |

This showed that Toyota have improved the tank-to-wheel efficiency of their Prius HEV from 30 to 37%, and hence the well-to-wheel efficiency from 26 to 32%. This puts it significantly (10%) ahead of their hydrogen FCHV at only 29%.

The above data (a) to (f) are not all for the same driving cycle - indeed (b) is for a trans-continental journey. However, they may be compared for tank-to-wheel efficiency to at least a first approximation by expressing each relative to that for a CV:

| Normalised Tank-to-Wheel Efficiencies | | | | | |
|---|---|---|---|---|---|
| Fuel | | Gasoline | Gasoline | Methanol | Hydrogen |
| Vehicle | | CV | HEV | FCV | FCV |
| (a) | ANL | 1 | 1.6 | | |
| (b) | DC NECAR 5 | 1 | | 1 | |
| (c) | Toyota I | 1 | 1.9 | | 3 |
| (d) | Ford P2000 | 1 | | | 1.9 |
| (e) | DC NECAR 4 | 1 | | | 1.8 |
| (f) | Toyota II | 1 | 2.3 | | 3 |

This shows that for tank-to-wheel efficiency, the new Toyota Prius HEV is second only to the Toyota hydrogen FCHV.

Likewise, the above data (a) to (f) may be compared for well-to-wheel efficiency - again to at least a first approximation - by expressing each relative to that for a CV: (The well-to-tank efficiency for producing methanol from natural gas has been taken as 0.7).

| Normalised Well-to-Wheel Efficiencies | | | | | |
|---|---|---|---|---|---|
| Fuel | | Gasoline | Gasoline | Methanol | Hydrogen |
| Vehicle | | CV | HEV | FCHV | FCHV |
| (a) | ANL | 1 | 1.6 | | |
| (b) | DC NECAR 5 | 1 | | 0.7 | |
| (c) | Toyota I | 1 | 1.9 | | 2.1 |
| (d) | Ford P2000 | 1 | | | 1.2 |
| (e) | DC NECAR 4 | 1 | | | 1.2 |
| (f) | Toyota II | 1 | 2.3 | | 2.1 |

This shows that for overall well-to-wheel efficiency, the new Toyota Prius HEV is significantly (10%) ahead of the Toyota hydrogen fuelled FCHV - and far ahead of all the others. It also appears that the Toyota FCHV has a well-to-wheel efficiency nearly twice that of the Ford P2000 and DC NECAR 4. This suggests that it is already fully developed, and that further significant improvement is unlikely.

Toyota have also reported that their hydrogen fuelled FCHV4 achieves a combined fuel economy on the US Federal Driving Cycle of 64 miles per kg of hydrogen. [64] This corresponds to about 64 miles per US gallon of gasoline on the LHV basis. The Honda FCX hydrogen fuelled FCHV has been tested by the US EPA. The 'window sticker' (corrected) fuel economy was city 51 and highway 48 miles per kg hydrogen. The uncorrected combined value is about 58 miles per kg hydrogen. This corresponds to about 58 miles per US gallon of gasoline on the LHV basis. Very similar to the NECAR 4 is the hydrogen fuelled DC A-Class 'Fuel Cell' - a short series produced for testing in California and elsewhere. The hydrogen consumption has been reported as equivalent to 4.2 litres of Diesel fuel per 100 km. [65] This corresponds to 50 mpg gasoline equivalent. These may be corrected for the differing upstream losses between hydrogen and gasoline to obtain relative well-to-wheel values. For the Toyota FCHV, 64 mpg ge becomes 64/1.52 = 42 mpg. For the Honda FCX FCHV, 58 mpg ge becomes 58/1.52 = 38 mpg. For the DC A-Class 'Fuel Cell', 50 mpg ge becomes 50/1.52 = 33 mpg. However, the 2004 Toyota Prius HEV with Hybrid Synergy Drive (HSD - also known as THS II) has a combined fuel economy of about 55 mpg. This value was given at the first showing in April 2003, and before testing by the EPA. [66] Compared directly with the Toyota FCHV (simply as both being 5-passenger vehicles), the well-to-wheel efficiency of the new Prius appears to be about 10% higher on (probably) the (slow) Japanese 10-15 driving cycle, and roughly 30% higher on the (faster) U.S. Federal driving cycle.

The tank-to-wheel efficiency is normally quoted for a specified driving cycle. If some of the cycle work is recovered by regenerative braking, the tank-to-wheel efficiency can exceed the cycle average engine thermal efficiency. Depending on the driving cycle, the potential braking energy recovery can be around 24 to 30%. [67] Moreover, the better the hybrid 'transmission' is at displacing the engine operating point from the road load line to the optimum operating line with low losses, the more closely the cycle average thermal efficiency approaches the best engine thermal efficiency. Hence the two effects together could result in the tank-to-wheel efficiency approaching - or even exceeding - the best engine thermal efficiency. The Prius Atkinson-cycle engine has the world's best thermal efficiency for a gasoline engine. [68] For the engine of the 1998 (Japanese market) Prius, it was 36.4% on the LHV, or 34.6% on the HHV. [69] It seems that for this driving cycle, with the new Toyota Prius and the Hybrid Synergy Drive, the engine best thermal efficiency is indeed exceeded by the tank-to-wheel efficiency of 37%. (It follows that over such a driving cycle, even a CV with an efficient diesel engine - but lacking regenerative braking - is likely to have a lower tank-to-wheel efficiency). The 2004 Prius has a relatively small - 1.5 litre - ICE, with a powerful 50 kW electric motor and battery, and is the result of over 10 years of R & D by Toyota, with 370 patents to show for it. Similar solutions were also found optimal for the GM Precept and Ford Prodigy HEVs developed during the US Partnership for a New Generation of Vehicles (PNGV) program. [70] However, the present U.S. administration cancelled the PNGV program when DC, Ford, and GM had produced only rolling prototypes that were nowhere near ready for production. Conversely, the 2004 Prius meets all the PNGV performance criteria and achieves 55 mpg, versus the 80 mpg fuel economy target, and Toyota will start selling it from October 2003.

Moreover, HEVs still have scope for improved hybridisation. The best thermal efficiency for gasoline may be e.g. 36.4% on the LHV. With braking energy recovery for the driving cycle of 30%, the net driving cycle work factor could be 0.7. The best thermal efficiency of ICEs occurs at fairly high power (e.g. 60%) - sufficient for high cruising speeds. Hence the transmission can displace the engine operating point from the road load line to the optimum operating line at high cruising speeds, and the average thermal efficiency factor could approach 1. Hence the tank-to-wheel efficiency for the driving cycle could approach 36.4/0.7 x 1 = 52% on the LHV.

However, FCVs have less scope for improved hybridisation. The best conversion efficiency of fuel cells occurs at fairly low power (e.g. 30%) - insufficient for high cruising speeds. Hence the transmission cannot displace the fuel cell operating point from the road load line to the optimum operating line at high cruising speeds, and the average conversion efficiency factor must then be significantly less than 1. Thus, even if the best conversion efficiency of a fuel cell system was higher than that of an ICE, the tank-to-wheel efficiency over the driving cycle may well be lower. While this could be overcome by increasing the power of the fuel cell, it would become even more expensive.

## 4) Vehicle Costs

Even if a case could be made for a particular new powertrain and fuel (e.g. on grounds of 'clean air'), these costs could represent very appreciable impediments to change. Only certain of the additional component costs have been considered.

Batteries

By far the most popular advanced automotive battery technology for BEVs, PHEVs, FCHVs and HEVs is Nickel Metal Hydride (NiMH). [71] [72] [73] As BEV examples, the weights of the NiMH battery packs of the Honda EV Plus and the Toyota RAV4 EV, with energy capacities of about 30 kWh, are somewhat under 500 kg (i.e. half a tonne). [74] For NiMH batteries, the nickel is itself expensive - both in energy cost and economic cost. 'For lower pricing than the above estimate at high volumes, a significant reduction in nickel metal pricing (which is independent of the battery market) and relocation of production to China or equivalent low labor/cost area would be required'. [75]

Because the battery of a BEV or PHEV is heavy and expensive, there is always the temptation to undersize it to reduce weight and cost. As a result, it may be cycled deeply - beyond 80% Depth Of Discharge (DOD) i.e. 20% State of Charge (SOC) - so that the cycle life is less than 1000, and the battery requires replacement during the life of the vehicle. Thus for BEVs and PHEVs, the cost of replacing the battery periodically may have to be added to the operating cost. For example, a Lead-Acid battery of 12 kWh may give a range of 50 miles, have a life of 200 cycles, and need replacing once a year at $ 1800. Alternatively, a NiMH battery of 28 kWh may give a range of 120 miles, have a life of 900 cycles, and need replacing once every 10 years, at $ 8400. Thus they would add $ 1800/(200 x 12) = 75 c and $ 8400/(900 x 28) = 33 c per kWh for each charge-discharge cycle. [76] This is roughly 12 or 5 times the probable cost of the electricity - so greatly increasing the running costs.

Fuel Cells

For FCVs, the fuel cells require for catalysis appreciable quantities of platinum metals, which are extremely expensive. An ADL cost analysis of a fuel processor and fuel cell of 50 kW assumed platinum weights of 30 and 181 g respectively. At $ 13.5/g, this was $2844. [77] Another ADL study put the overall platinum content of a fuel cell powertrain as 4 grams per kW, which at current prices represented a cost of $ 60/kW. [78] Assuming a powertrain maximum net output of 50 kW, this would mean 4 x 50 = 200 g, and cost $ 3000. Although FCVs fuelled with hydrogen would require no fuel processor and hence somewhat less platinum, these costs are indicative. However, ADL say that 'a further reduction (of the platinum content) by a factor of 5 or 10 appears both possible and necessary...'. The World Fuel Cell Council has published estimates of platinum use for car-sized fuel cell systems: Current 100 g, Serious production 40 g, Mass production 20 g, Ultimate target in US 9 g. [79] Whether the lower values can be reached, while still meeting the efficiency and operating lifetime objectives, remains to be demonstrated.

Catalytic Converters

For the exhaust catalytic converters in CVs and HEVs, the weight of platinum group metals (PGM) may be estimated. The ratio of catalyst volume/engine displacement is from 0.7 to over 1.0, and the typical catalyst loading on current LEVs and ULEVs ranges from below 50 up to 300 g/ft3. [80]
With an engine of 1.5 l = 90 in3 = 0.052 ft3, and a loading of 100 g/ft3, the PGM would be about 5.2 g.
With an engine of 6 l = 360 in3 = 0.208 ft3, and a loading of 300 g/ft3, the PGM would be about 62 g.

Material Abundance

Platinum metals (platinum, palladium, and rhodium) have very limited abundance in the earth's crust. Moreover, they have many other uses - including as catalysts in the chemical industry, and for automobile catalytic converters. Hence for FCVs fuelled with hydrogen, there may not be enough platinum available - even with extensive recycling. At the maximum, this could be for all the road vehicles in the world. This was about 740 million in 2000, and is expected to be about a billion in 2020. [81] Indeed, there may not even be enough for the U.S. light vehicle fleet.

A study by ADL for the US DOE considered a fuel cell stack producing 50 kWe net. [82] They estimated the platinum required for each stack as 180 g, hence for 500,000 vehicles as some 90 tonnes. Yet they gave the 1996 annual production as only 73 tonnes, and the 1995 estimated reserves as 5000 tonnes. At this rate, the world platinum reserves would be enough for only 28 million vehicles - only about twice the California light vehicle fleet, and less than a sixth of the US light vehicle fleet. It has been claimed that the platinum content could be reduced by a factor of 5 or 10. [83] Even then the quantities required would still represent large shares of the reserves, and the price would be correspondingly high.

However, another authority has quoted Professor R. Grant Cawthorn, of the Department of Geology of Witwatersrand University in South Africa, in 1999, as putting the reserves in the ground at 1.5 billion troy ounces (i.e. about 47,000 tonnes). [84] This is nearly ten times as much, and - if correct - would greatly ease any availability and price constraints.

Whether limited by cost or abundance, it is worth considering where best to deploy the platinum group metals (PGM). Exhaust catalysts are already fitted to over half of the cars in the world, and to about 80% of new cars. [85] The ratio of PGM per vehicle for FCVs to that for CVs and HEVs could be from 200/62 = about 3 or 20/5.2 = about 4, to 200/5.2 = about 40. Since PGM in the exhaust catalysts of CVs and HEVs can reduce emissions to insignificant levels, their use in FCVs - which require more per vehicle - would be less effective in reducing total regulated emissions.

**5) Vehicle Engineering and Manufacturing Plant Costs**

Cost of Engineering Resources

Only about 600 of the GM EV1 BEVs were leased, yet the program allegedly cost GM $ 300 million, [86] or even a billion dollars. [87] This gives a unit cost of at least about $ 500,000 each - very little of which was recovered via the leasing charges. In the light of this, manufacturers will look extremely critically at any proposal for alternative powertrains before committing their limited financial and engineering resources.

Cost of New Manufacturing Plant

Adopting BEVs, PHEVs or FCVs would involve leaving stranded vast assets, some of which are intended to be used for 20 years or more. They would imply writing off some or all the plant for manufacturing internal combustion engines and transmissions - a huge past investment. Moreover, BEVs, PHEVs, or FCVs would imply full sized (e.g. 75 kW) motors - a huge new investment - and possibly large batteries (e.g. 30, 6, or 2 kWh respectively) - another huge investment. Dr Kalhammer of the Battery Panel has been quoted as saying that a battery plant capable of 20-40,000 packs per year would cost $ 40 to 100 million. [88] FCVs would also imply plant to manufacture fuel cell stacks and the many complex sub-systems - another huge investment.

Yet BEVs and FCVs would be not be saleable world-wide, due to the lack of an adequate charging or hydrogen fuelling infrastructure. Since all vehicle manufacturers - both US- and foreign-owned - must sell overseas to achieve competitive economies of scale, this would put them at a disadvantage - which in practice they would resist very strongly. Moreover, several of the major US manufacturers are already deep in debt - e.g. Ford owes some $ 230 billion. [89] Conversely, HEVs would continue to use existing internal combustion engine manufacturing plant, and only require new plant for part-size (e.g. 50 kW) motors and small (e.g. 1 to 2 kWh) batteries. This may explain Toyota having sold over 120,000 of the original Prius HEV - which they say is profitable [90] - and having just announced a new and significantly improved model for 2004, and plans for more new HEVs in 2005 and beyond. [91]

Cost of Fleet Replacement

For BEVs, PHEVs and FCHVs, since conversion is impractical, the entire light vehicle fleet would have to be replaced. This would be an enormous cost and would take at least 15 years - the turnover time. This would be business for the vehicle manufacturers, but the cost would fall on the purchasers. Assuming that the US light vehicle fleet numbers 170 million, and an average vehicle price at retail of $ 20,000, the replacement cost would be $ 3400 billion or $ 3.4 million million - i.e. over three trillion dollars.

Existing CVs could use up to 23% ethanol without modification, and existing high-volume CVs could be converted to FFVs - to use up to E85. (The major engine families would require only simple modifications to enable them to run on 0 to 85% ethanol). More new CVs could be shipped as FFVs very soon, since it is current technology, and very low (less than $200) in cost. New HEVs could be shipped as FFVs very soon, since it is current technology, and very low (less than $200) in cost. While HEVs cost more than CVs, this premium is falling, and would be justified by the fuel savings. Hence for CVs and HEVs to use up to 85% ethanol, the vehicle fleet could change over at its natural rate, at little additional cost.

**5) Fuel Infrastructure Costs**

Some believe that BEVs could be charged - without the need for additional plant - by using the off-peak capacity of the existing electricity supply system. If all vehicles were BEVs, they would require additional power station capacity of roughly three times. So existing power stations might (if doing nothing else) support one third of the vehicle fleet. The average load factor on an electric system is around 0.5. Hence the off-peak energy available is up to half of the theoretical continuous capacity. Thus off-peak capacity from existing power stations might support one sixth of the vehicle fleet. However, the energy would still have to be paid for, and whether the existing transmission and distribution system could support even this fraction is another matter.

Cost of Electricity Transmission and Distribution Plant

For BEVs on any significant scale, additional electric energy would be needed for re-charging the batteries, and this would require additional electric power capacity. If the BEV energy consumption is say 3 miles/kWh, [92] then for say 20 miles added per day, this is 20/3 = 6.7 kWh/d. With a battery charge-discharge efficiency of say 90%, [93] and a charger efficiency of say 85%, [94] this becomes 8.7 kWh/d from the wall socket. With an off-peak period of 8 hours, the average charging power would be about 1.1 kW. Assuming that other electricity use per household is at least 4500 kWh/y, this is only 4500/8760 = 0.5 kW or even double for large US appliances, and air conditioning = 1.0 kW. Hence during the off-peak period, re-charging an electric car could increase the average load per household from 0.5 or 1 to about 2 kW. Although each dwelling may be fused to say 60 amp x 220 volts = 13 kW, the generation, transmission and distribution system would certainly not be able to meet this for all - or even anything like all - households at once. This is because such systems are sized assuming a 'diversity factor', which may be 0.7 or lower. While re-charging of some cars may be possible without additional investment, this is not a solution. A solution must be widely replicated, and this would require a corresponding investment. Yet some households may require even more vehicle miles per day. Hence BEVs and PHEVs would require massive reinforcement of the power transmission and distribution systems. However, this is hard to quantify in general terms. The requirements and costs would have to be determined for specific systems.

Cost of a Hydrogen Infrastructure

FCVs would require a new infrastructure for the production, distribution, and storage of hydrogen. For the equivalent of 1 million bbl/day of gasoline and diesel fuel, Exxon have quoted others who put it at $100 billion. [95] (This is about the usage in the UK). Hence for the equivalent of 10 million bbl/day, it might be one trillion dollars. (This is about the usage in the USA). Assuming that there are about 170 million vehicles in the USA, this would amount to an investment of roughly $ 5,900 for each. An ANL study gives the cost of a hydrogen production (using natural gas) and distribution infrastructure for 60% of the vehicle fleet - i.e. 100 million vehicles - as $ 500 billion or more. [96] But even this would not be sustainable. A comparable infrastructure that used renewable electricity to produce the hydrogen sustainably would cost even more.

Cost of Electricity Generating Plant

In most developed countries, electricity accounts for only about 18% of end use, where transport fuels account for about 34%, and heat for about 48%. [97] Hence to replace transport fuels by electricity for BEVs - even on a simplistic view, ignoring efficiencies - would require that the electricity capacity be 1 + 2 = 3 times as large. Moreover, if hydrogen was used for FCVs, the additional capacity required for electricity and hydrogen production could be double, to make it 1 + 2 x 2 = 5 times as large. Indeed, the power station capacity needed to replace present transport fuels with hydrogen has been estimated as about a three to five-fold increase. [98]

Availability of Ethanol from Renewable Sources

To judge ethanol as a sustainable solution, the issue is availability - rather than matching the present low US gasoline prices, which are not sustainable. 'Ethanol is a renewable resource' and 'over 1.4 billion gallons were produced in 1998 from 55 facilities in the US'. [99] 'The ethanol industry is expected to produce more than 2.6 billion gallons in 2003. Currently 70 ethanol plants have the capacity to produce over 2.75 billion gallons annually. Ten additional plants are under construction'. [100] Indeed, the US capacity for bio-ethanol from corn is expected to be just under 4.5 billion gallons a year in January 2004. [101] Moreover, ORNL conservative estimates predict (additional) ethanol production from cellulose feedstocks may reach 3 to 4 billion gallons a year in 10 years (enough for at least 10 million FCVs) and 8 billion gallons a year in 20 years (enough for 20 million FCVs). Best case scenarios project substantially higher numbers. [102] As noted above, FCVs could with advantage be replaced by HEVs.

It has been shown - quantitatively - that HEVs and bio-ethanol for road transport could be part of a solution to reduce carbon dioxide emissions by 60 % (in 2050) for the UK - and hence other countries. [103] In a national study of future gaseous and liquid fuels, bio-ethanol is seen as a favoured candidate in the Netherlands. [104] It has also been identified as a primary candidate vehicle fuel in a Swedish study. [105] Moreover, Shell is considering a £ 100 million plan to build a commercial plant to turn wood shavings and other farm waste into a 'green' fuel for British motorists. Furthermore, such bio-ethanol would produce 90% less greenhouse gas emissions than gasoline. [106]

The world production of petroleum in 1998 was about 3500 million tonnes oil equivalent (mtoe) - of which about 20 % was used for transport. The potential annual world production of bio-ethanol from starch-sugar crops is roughly 500 mtoe, of which 67 mtoe is in the EU (15). Hence 500 mtoe would be equivalent to about 71 % of the 1998 transport demand. Production from lignocellulosic biomass is under very active R & D. If this succeeds, the world potential would be about 1300 mtoe, equivalent to almost twice the 1998 world transport demand. [107] Even with other uses and without any efforts at saving transport fuels, this should suffice for some future growth in demand. If the land area was insufficient, or the cost of feedstock too high, more ethanol could be synthesised from renewable hydrogen and captured carbon dioxide (e.g. from power station flues), and emit little or no net carbon in use.

## 7) Discussion

Regulated emissions.

Instead of a prescriptive ZEV Mandate, the California fleet average emissions requirement could be met (as with the earlier LEV Program) with vehicles certified as TLEV, LEV, ULEV, and SULEV. Even the reduced fleet average requirement for 2010 and beyond could be met with a mix of 55% ULEV and 45% SULEV. The vehicle manufacturers could then choose solutions for California that are compatible with their products for other markets.

CVs of several vehicle types already meet the California SULEV standard. Even lower emissions can be achieved with HEVs. In theory series HEVs would give the best results, but with two full size electrical machines, these would be expensive. Parallel HEVs are a good compromise, achieving effective shielding of the ICE from transients, but with smaller electrical machines. Series-parallel HEVs (like the Toyota Prius) are an even better compromise, and over 120,000 have been sold at a profit in several markets. Toyota has announced that production of the 2004 Prius HEV will be tripled to 72,000 a year. Moreover, with additional models - including a Lexus RX330 SUV in 2005 - Toyota HEVs should total 300,000 a year by 2006. [108] Indeed, Toyota foresee a complete transition of their vehicles to HEVs by 2012. [109] Honda is producing a 'mild' hybrid version of the Civic. In addition, Ford have announced that an HEV version of the Escape SUV will be available in 2004/5, and Nissan will launch an HEV for 2006.

With the cost being lower, and the deployment much faster, than of BEVs or FCVs, this means that HEVs can give the fastest and greatest improvement in total regulated emissions - and hence in air quality. Clearly the marketplace and evolving technology are the most efficient way of allocating scarce resources. Several major vehicle manufacturers are deep in debt, and in no position to strand their existing manufacturing assets, and/or buy new ones - even on the scale implied by the present ZEV mandate.

It seems that there is a growing awareness within CARB that HEVs now are preferable to FCVs maybe later. Jerry Martin was quoted as saying 'Hybrids are here now'. 'There's going to be over three million of them (projected) by 2011. You get some fairly significant impact in a short period of time. It's a very cost-effective, very efficient savings that could happen right now - is happening right now'. (Conversely), 'We're talking 2012 before significant numbers of (hydrogen-fuelled fuel cell) vehicles are on the streets'. The board staff is considering rewriting the regulations to add new requirements for hybrids and other cars with cleaner emissions as a way to immediately cut pollution from internal combustion engines. [110]

Plant for the production and distribution of bio-ethanol would certainly be of use to the existing CV and HEV fleet, and as the number of FFVs increases. Conversely, a ZEV mandate would imply enormous outlays on infrastructure (i.e. plant for electricity for BEVs and plant for hydrogen for FCVs), but no certain return. Indeed, the costs could prove prohibitive, and the mandate cancelled sooner or later. Furthermore, for much lower cost and risk than ZEVs and their infrastructure, any jurisdiction should be able to build an efficient mass transit system, which could greatly reduce light vehicle traffic - so reducing emissions and energy consumption and increasing sustainability.

Energy and Fuel Usage

For electricity supply systems like that of the USA, with large amounts generated from fossil fuels, the well-to-wheel efficiency for BEVs is much lower than for HEVs. PHEVs attempt to serve as BEVs and HEVs. However, having an engine, a large motor and a larger battery, they would be at least as expensive as a BEV, while compromising the HEV function. Hence the well-to-wheel efficiency of PHEVs of any electric range would be even lower that that of a BEV. One reason is that the additional weight of the battery impairs the energy efficiency in HEV mode, and the weight of the engine impairs the energy efficiency in BEV mode. Moreover, if widely deployed, they would also require costly additions to the electricity generation, transmission and distribution infrastructure.

Most proponents of hydrogen have failed to consider the upstream processes - especially longer term - beyond its production from natural gas. They have also assumed that FCVs would have a good tank-to-wheel efficiency and thus the combination a good well-to-wheel efficiency. Measured well-to-wheel efficiency data has shown that, compared with a hydrogen fuelled Toyota FCHV, that of a gasoline Toyota HEV with HSD (THS II) - the 2004 Prius - is higher by 10 to 30%. Moreover, this finding is supported by several other measurements. Even when derived from natural gas, the production of hydrogen would generate a great deal of carbon dioxide, which would need to be captured and sequestered - at considerable cost and some risk. Yet since all fossil fuels are finite, it would not be sustainable.

To effect really major reductions in petroleum use and carbon dioxide emissions, a transition to renewable fuels is required. If the hydrogen was produced by electrolysis, the well-to-tank efficiency would be only 50% at best, and thus the well-to-wheel efficiency of the FCV would be even lower. [111] Furthermore, any leakage would represent a corresponding loss of energy and thus of well-to-wheel efficiency. [112] Yet renewable electricity would be better used to displace coal and gas fired generation, than for charging Battery Electric Vehicles or making hydrogen for Fuel Cell Vehicles. [113] [114]

Therefore - compared with the best full HEVs - ZEVs (BEVs, FCVs, and perhaps PHEVs) would actually increase energy use. As to the effect of ZEVs on petroleum use and carbon dioxide emissions, this would depend on the number of vehicles. Deploying ZEVs on the scale proposed would offer no reduction in petroleum use and carbon dioxide emissions by 2020. However, if instead full HEVs were deployed, then - due to their lower initial costs - the numbers sold could be larger and the reduction in energy use greater. Moreover - like the existing CVs - HEVs could use more (than the existing 10%) bio-ethanol blended with gasoline in California, which would further reduce petroleum use and carbon dioxide emissions.

Vehicle and Fuel Infrastructure Costs

CARB accepts that at present FCVs cost a million dollars each. [115] The president of Honda has been quoted as saying that he expects to build one FCHV a month over the next two or three years. Also, a Honda engineer is reported to have said that a great effort would be needed to bring the cost of a FCHV down to $ 100,000.[116] Toyota's FCHV cost 100 million yen (about $ 842,000) to build, according to Taiyou Kawai, general manager of Toyota's fuel cell R & D department. 'It won't be anytime soon for mass commercialisation. It will maybe take us another 10 years'. [117] Many in the US research community also have their doubts about any commercialisation of FCVs - either by 2020 or indeed ever. [118]

Outside the USA, and especially California, there are far fewer two-car families. Therefore cars have to be more capable. There would be a much smaller market for BEVs with limited range - to sit alongside a conventional (gasoline or diesel) car. Moreover, BEVs and FCVs would be even less attractive outside California - due to the vehicle and infrastructure costs involved. Even with some assembly plants, California is probably still a net importer of vehicles (as is the UK). Furthermore, the balance would be even worse for territories - developed as well as developing countries - with no assembly plants. They would have no profits from the sales of new vehicles to offset the very high costs of infrastructure and operation. Hence these markets would be unwilling to pay for the new infrastructure for electricity and hydrogen, and would be closed to such vehicles.

Conversely, the use of bio-ethanol (as E10, E23, and E85) in existing and new CVs and HEVs could be implemented at much less cost and in much less time. [119] To lower further the time and cost of the transition, FFV conversion kits (to enable the use of E85) could be developed for existing vehicles - at least for high volume models/engines. Furthermore, since every country could produce or import bio-ethanol, such Flexible Fuel CVs and HEVs would be saleable world-wide, and this solution would be far more sustainable.

## 8) Conclusions

Battery Electric Vehicles and Fuel Cell Vehicles (certified as Zero Emission Vehicles) could not meet the California objectives - reduced regulated emissions, petroleum usage, and carbon dioxide emissions - especially in the longer term. However, Conventional Vehicles and Hybrid Electric Vehicles (certified as ULEV and SULEV) could meet all the objectives - helped by increasing proportions of bio-ethanol fuel.

Regulated Emissions

The marginal effectiveness of Battery Electric Vehicles and Fuel Cell Vehicles means that their total impact would be insignificant - especially if their high cost reduced their deployment below even the small scale envisaged. After all, the SULEV standard was set to be close to the (electric power plant) emissions of a BEV, and HEVs can now achieve regulated emissions some 72% lower. Moreover, the California fleet average requirements for regulated emissions - even for 2010 and beyond - could be met with a mix of Conventional Vehicles and Hybrid Electric Vehicles certified as ULEV (55%) and SULEV (45%). Furthermore, the relatively low cost of these powertrain options means that the total impact would be much faster and greater. It seems that this is now appreciated within the California Air Resources Board.

## Petroleum Use and Carbon Dioxide Emissions

Analysis of actual measured data shows that both Battery Electric Vehicles and hydrogen Fuel Cell Hybrid Vehicles have lower well-to-wheel efficiencies than 'full' Hybrid Electric Vehicles. Moreover, leakage of hydrogen would further lower efficiency and increase carbon dioxide emissions. Conversely, bio-ethanol is being produced and used as automotive fuel on an increasing scale, and with ever-less fossil energy input, in the USA and world-wide. Since existing Conventional Vehicles and Hybrid Electric Vehicles can use blends of up to 23%, and Flexible Fuelled Vehicles (both CVs and HEVs) could use blends of up to 85%, the impact on petroleum use and carbon dioxide emissions would be much faster and greater. This should be encouraged by adjusting taxes to make E85 consistently less expensive than gasoline not on a volume, but on an energy basis.

## Vehicle, Manufacturing, and Fuel Infrastructure Costs

For Battery Electric Vehicles or Fuel Cell Vehicles, the increased vehicle costs would be very considerable and the cost of replacing even a significant proportion of the vehicle fleet would be huge. Also the capital costs for new manufacturing plant would be huge. Yet several major vehicle manufacturers are deep in debt.

For Battery Electric Vehicles, roughly tripling of the plant required for generation, transmission, and distribution of electricity would be required. Moreover, for Fuel Cell Vehicles, the costs of a hydrogen infrastructure, and of a further doubling of the electricity generating plant would be required. These costs would be yet higher if the plant used renewable sources - for greater sustainability. Since these costs would be prohibitive, Battery Electric Vehicles and Fuel Cell Vehicles would be unsaleable world-wide.

Conversely, Conventional Vehicles and ICE Hybrid Electric Vehicles would be only marginally more expensive, and could be fuelled with increasing amounts of bio-ethanol, while using the existing liquid fuel infrastructure - and hence sold world-wide.

## Sustainability

Millions of Conventional Vehicles are already fuelled with bio-ethanol (E23 and E100) in Brazil and (E10) in the USA, and - as Flexible Fuel Vehicles - can be fuelled with bio-ethanol (E85) in the USA. They provide a proven route to sustainability. Other countries, such as Sweden, are producing and using bio-ethanol (E85) on an increasing scale for the same reason. All countries could produce or import bio-ethanol. Moreover, the potential world bio-ethanol resource is sufficient to fuel all the existing road vehicles. Hence Conventional Vehicles and Hybrid Electric Vehicles could be increasingly fuelled with bio-ethanol, which can use the existing liquid fuel infrastructure, making it increasingly sustainable. Thus Conventional Vehicles and Hybrid Engine-Electric Vehicles could continue to be sold world-wide.

[1] (Ref. http://www.hubbertpeak.com/campbell/commons.htm).
[2] (Ref. EPA 420-B-00-001, February 2000, and Toshio Inoue et al, Toyota, 'Improvement of a Highly Efficient Hybrid Vehicle and Integrating Super Low Emissions', SAE Paper 2000-01-2930).
[3] (Ref. R.B. Farrington et al, 'Challenges and Potential Solutions for Reducing Climate Control Loads in Conventional and Hybrid Electric Vehicles', NREL. 'vmtsfinalsent.pdf').
[4] (Ref. CARB, Staff Report, July 1997, p 5. 'staffrep.pdf').
[5] (Ref. CARB, Staff Report, July 1997, p 5. 'staffrep.pdf').
[6] (Ref. CARB, Staff Report, July 1997, p 14. 'staffrep.pdf').
[7] (Ref. htttp://www.epa.gov/otaq/regs/ld-hwy/tier-2/frm/f99051.htm).
[8] (Ref. ANL, 'PSAT (Powertrain Systems Analysis Toolkit)', 25 February 2003, https://www.psat.anl.gov/default).
[9] (Ref. CARB, LEV II Report, June 19, 1998, p 23, 'pstfrpt.pdf').
[10] (Ref. ADL, 'Fuel Cycle Energy Conversion Efficiency Analysis', CEC, May 2000, '2000-05-15_500-00-24.pdf').
[11] (Ref. Joan M. Ogden, 'Developing an infrastructure for hydrogen vehicles: a Southern California case study', Intl. Jl. Hydrogen Energy, 24 (1999) 709-730. 'Developing_infrastructure_hydrogen.pdf').
[12] (Ref. CARB, 'Proposed Amendments to the Zero Emission Vehicle Regulation', March 27, 2003, April 24, 2003, Slide 39. 'staff.pdf').
[13] (Ref. 'ARB Modifies Zero Emission Regulation', CEPA, April 24, 2003, 'http://www.arb.ca.gov/newsrel/nr042403.html).
[14] (Ref. ADL, 'Benefits of Reducing Demand for Gasoline and Diesel', March 28, 2002, p 14. '2002-04-12_CARB_REPORT.PDF').
[15] (Ref. 'California's Line in the Sand', July 27, 2002, http://evworld.com/storybuilder.cfm?storyid=388).
[16] (Ref. 2004 Prius document, Glossary. http://www.toyota.com/prius/minisite/html/printable.html).
[17] (Ref. CARB document).
[18] (Ref. 'Focus FCV: Next Step Production', http://evworld.com/databases/printit.cfm?storyid=333).
[19] (Ref. Norihiko Nakamura, 'Working Towards Market Introduction of FC Vehicles', Future Car Congress 2002, June 3, 2002, 'nakamura.pdf').
[20] (Ref. 'Ethanol', 'http://www.ccities.doe.gov/vbg/consumers/e85.shtml).
[21] (Ref. 'Miljobilar 6 01.pdf', 2001, p 4).
[22] (Ref. NREL & NEVC, 'Handbook for Handling, Storing and Dispensing E85', p 7, 'http://www.e85fuel.com/pdf/ethanol_guidebook.pdf').
[23] (Ref. CARB, LEV II Report, June 19, 1998, p 22. 'pstfrpt.pdf').
[24] (Ref. ADL, 'Benefits of Reducing Demand for Gasoline and Diesel', CARB, March 28, 2002, p 2-18. '2002-04-12_CARB_REPORT.PDF').
[25] (Ref. Buyers Guide to Cleaner Cars, http://www.arb.ca.gov/msprog/ccbg/ccbg.htm).
[26] (Ref. CARB, '2000 Zero Emission Vehicle Program Biennial Review', August 7, 2000, p ix. 'staffreportfinal.pdf')
[27] (Ref. Dr. Abthoff et al, 'The Mercedes-Benz C-Class Series Hybrid', EVS 14 paper).
[28] (Ref. http://epa.gov/otaq/crttst.htm).
[29] (Ref. Toshio Inoue et al, Toyota, 'Improvement of a Highly Efficient Hybrid Vehicle and Integrating Super Low Emissions', SAE Paper 2000-01-2930).
[30] (Ref. CARB, 'Proposed Amendments to the Zero Emission Vehicle Regulation, March 27-28, 2003', Slide 36, 'staff.pdf').
[31] (Ref. http://www.mototrend.com/future/spied/112_fvfmain/)
[32] (Ref. http://greet.anl.gov/default.htm).
[33] (Ref. http://www.hubbertpeak.com/campbell/commons.htm).
[34] (Ref. ADL, 'Fuel Cycle Energy Conversion Efficiency Analysis', CEC, May 2000, p 16, '2000-05-15_500-00-24.pdf').
[35] (Ref. H. Shapouri et al, 'The Energy Balance of Corn Ethanol: An Update', USDA Report No. 813, July 2002, 'aer-813.pdf').

[36] (Ref. US DOE, 'The US Dry-Mill Ethanol Industry', 2001, 'drymill_ethanol_industry.pdf' and work at ORNL and NREL).
[37] (Ref. D. Lashof et al, 'Dangerous Addiction 2003', NRDC, March 2003, p 9, 'da2003.pdf').
[38] (Ref. http://ctts.nrel.gov/analysis/advisor.html)
[39] (Ref. Toshio Inoue et al, Toyota, 'Improvement of a Highly Efficient Hybrid Vehicle and Integrating Super Low Emissions', SAE Paper 2000-01-2930).
[40] (Ref. CARB '1998 Zero-Emission Vehicle Biennial Program Review', July 6, 1998, p 27. 'staffrpt.pdf').
[41] (Ref. Feng An et al, 'Evaluating Commercial and Prototype HEVs', SAE paper 2001-01-0951).
[42] (Ref. ANL, 'Hybrid Electric Vehicle Technology Assessment: Methodology, Analytical Issues, and Interim Results', ANL/ESD/02-2, October 2001, p 62. '244.pdf').
[43] (Ref. Mark Alexander et al, 'A Mid-Sized Sedan Designed for High Fuel Economy and Low Emissions: The 1999 UC Davis FutureCar', p 7. 'UCD Tech Report1999.pdf').
[44] (Ref. ADL, 'Projected Automotive Fuel Cell Use in California', October 2001, p 11, CEC Report P600-01-022F, '2002-02-06_600-01-022F.PDF').
[45] (Ref. Toyota, Special Report 10).
[46] (Ref. ADL, Cost Analysis of Fuel Cell System for Transportation', March 2000, p 53. 'baseline_cost_model.pdf').
[47] (Ref. R.B. Farrington et al, 'Opportunities to Reduce Vehicle Climate Control Loads', NREL. 'evs15paper.pdf').
[48] (Ref. DTI, DUKES 2001, Chap. 5. http://www.dti.gov.uk).
[49] (Ref. F. Badin et al, 'Hybrid Vehicles, should we plug them to the grid or not ?', EVS 18, 2001, p 9).
[50] (Ref. CARB document).
[51] (Ref. Joan M. Ogden, 'Fuels for Fuel Cell Vehicles', Fuel Cells Bulletin No 16, January 2000. 'Fuel_Fuel_Cell.pdf').
[52] (Ref. ADL, 'Fuel Cycle Energy Conversion Efficiency Analysis', CEC, May 2000, Fig. 8, '2000-05-15_500-00-24.pdf').
[53] (Ref. EPA, 'Fuel Economy Guide - Alternative-fuelled Vehicles'. '99guid889.xls')
[54] (Ref. EPA, 'Fuel Economy Guide - Alternative-fuelled Vehicles'. '00guide.xls').
[55] (Ref. GM et al, North American Analysis, April 2001. '163.pdf' and European Analysis, 27 September 2002. 'TheReport_Euro-WTW_27092002.pdf').
[56] (Ref. M. A. Weiss et al, 'On the Road in 2020', MIT Energy Lab., October 2000. 'e100-003.pdf').
[57] (Ref. N. Owen et al, 'Carbon to Hydrogen Roadmaps for Passenger Cars', Ricardo, 8 November 2002. 'carbon.pdf').
[58] (Ref. Feng An, SAE paper 2001-01-0951 and 'Evaluating Commercial and Prototyped HEVs'. '89.pdf').
[59] (Ref. John Gartner, 'Fuel Cell Car Coasts Across U.S.', June 5, 2002. http://www.wired.com/news/print/0.1294.52877.00.htm).
[60] (Ref. Norihiko Nakamura, 'Working Towards Market Introduction of FC Vehicles', Future Car Congress 2002, June 3, 2002. 'nakamura.pdf').
[61] (Ref. ADL, 'Projected Automotive Fuel Cell Use in California', October 2001, p 15, CEC Report P600-01-022F. '2002-02-06_600-01-022F.PDF').
[62] (Ref. Norihiko Nakamura, 'Working Towards Market Introduction of FC Vehicles', Future Car Congress 2002, June 3, 2002. 'nakamura.pdf').
[63] (Ref. Toyota 'specialreports_12.pdf', May 2003)
[64] (Ref. Alec Brookes, 'Fuel Cell Disruptor', http://www.evworld.com, quoting Mr Norihiko Nakayama speaking at the 2002 Future Car Congress).
[65] (Ref. 'Customers test the A-Class with fuel cell drive', 2003-01-14. http://www.h2cars.biz/artman/publish/printer_77.shtm).
[66] (Ref. 'Toyota unveils new version of Prius hybrid car'. http://www.forbes.com/business/energy/newswire/2003/04/16/rtr942450.html)
[67] (Ref. ANL, 'Hybrid Electric Vehicle Technology Assessment: Methodology, Analytical Issues, and Interim Results', ANL/ESD/02-2, October 2001, p 25. '244.pdf').

[68] (Ref. http://www.toyota.co.jp/Irweb/corp_info/pr/2003/0417d.htm).
[69] (Ref. Michael Duoba et al, 'In-Situ Mapping and Analysis of the Toyota Prius HEV Engine', ANL, SAE paper 2000-01-3096).
[70] (Ref. Feng An et al, 'Evaluating Commercial and Prototype HEVs', SAE Paper 2001-01-0951).
[71] (Ref. CARB, '1998 ZEV Program Biennial Review', July 6, 1998, p 33. 'staffrpt.pdf').
[72] (Ref. CARB, Battery Panel report, June 22, 2000, p vi. 'btapreport.pdf').
[73] (Ref. CARB, '2000 ZEV Program Biennial Review', August 7, 2000, p v. 'staffreportfinal.pdf').
[74] (Ref. CARB, '1998 ZEV Program Biennial Review', July 6, 1998, p 25. 'staffrpt.pdf').
[75] (Ref. M. Anderman, 'Brief Assessment Report for CARB, 2003. 'andermanreport.pdf').
[76] (Ref. '1998 ZEV Program Biennial Review', CARB, p 34. 'staffreport.pdf').
[77] (Ref. ADL, Cost Analysis of Fuel Cell System for Transportation', March 2000, p 53. 'baseline_cost_model.pdf').
[78] (Ref. ADL, 'Projected Automotive Fuel Cell Use in California', October 2001, p 9, CEC Report P600-01-022F. '2002-02-06_600-01-022F.PDF').
[79] (Ref. Fuel Cell Today, 'Fuel cells promise brave new world for platinum', 27 Nov 2002).
[80] (Ref. 'LEV II Report', CARB, June 19, 1998, p 43. 'pstfrpt.pdf').
[81] (Ref. Hiroyuki Watanabe, 'Accelerating towards a Hydrogen Society through Fuel cell Vehicles'. http://toyota.co.jp/Irweb/special_rep/fchv/fchv_1.html).
[82] (Ref. ADL, 'Cost Analysis of Fuel Cell System for Transportation', March 2000, slide 24. 'baseline_cost_model.pdf')
[83] (Ref. ADL, 'Projected Automotive Fuel Cell Use in California', October 2001, p 10, CEC Report P600-01-022F, '2002-02-06_600-01-022F.PDF').
[84] (Ref. World Fuel Cell Council, 'Platinum availability for Fuel Cells', 2000).
[85] (Ref. http://www.mathey.com/environment/cuttingpollution/02.html).
[86] (Ref. Jim Motavalli, 'Forward Drive', Sierra Club Books, 2000, p ???)
[87] (Ref. CBS Evening News, 'GM Pulls Plug On Electric Car', March 11, 2003. http://cbsnews.com/stories/2003/03/11/eveingnews/main543605.shtml).
[88] (Ref. K. Maruo, 'Driving from Memorandum to Momentum - Electric Vehicle Development after March 1996', EVS14 paper, 1995, p 2).
[89] (Ref. Jennifer Ryan, Bloomberg New, 'Ford asset-backed plan may hurt ratings, Moody's says', http://www.detnews.com/2003/autoinsider/0304/30/autos-15185.htm).
[90] (Ref. http://www.catiaworld.com/lang1/mem/news/arc/_disc2n/00000061.htm).
[91] (Ref. New York Auto Show - Don Esmond, http://pressroom.toyota.com/photo_library/display_release.html?id=sp20030418b).
[92] (Ref. CARB document ?),
[93] (Ref. CARB document).
[94] (Ref. F. Badin et al, 'Hybrid Vehicles, should we plug them to the grid or not ?', EVS 18, 2001, p 9).
[95] (Ref. Exxon, SAE paper 2000-01-0003, p 16).
[96] (Ref. Marianne Mintz et al, 'Cost of Some Hydrogen Fuel Infrastructure Options', ANL, January 16, 2002. '244.pdf').
[97] (Ref. UK DTI, 'ecuk.pdf').
[98] (Ref. U. Bossel et al, 'The Future of the Hydrogen Economy: Bright or Bleak ?', 15 April 2003, p 26, http://www.efcf.com/reports).
[99] (Ref. ADL, 'Projected Automotive Fuel Cell Use in California', October 2001, p 7, CEC Report P600-01-022F. '2002-02-06_600-01-022F.PDF').
[100] (Ref. 'RFA ethanol report', March 2003. http://www.ethanolrfa.org/ereports/er032403.html).
[101] (Ref. 'US Ethanol Industry Production Capacity Outlook', July 18, 2002, Fig. 1. '2001-08-29_600-01-017.PDF').
[102] (Ref. J. Bentley et al, 'Ethanol and Fuel Cells: Converging Paths of Opportunity', Renewable Fuels Association, 2002. 'RFA_Fuel_Cell_White_Paper.pdf').
[103] (Ref. Gordon Taylor, 2003, http://www.thermal.demon.co.uk/epolicy.htm).
[104] (Ref. ADL, 'Analysis and Evaluation of GAVE Chains', GAVE Report 9921, December 1999, p 7. 'ADL1.pdf').

[105] (Ref. Ecotraffic 'Sustainable Fuels', Vagverket Publication 2002:144, p iv. '2002_144.pdf').
[106] (Ref. Guardian of London, 'Shell Green Fuel in UK Pipeline', 2002-05-10. http://www.evworld.com).
[107] (Ref. G. Grassi, 'Bioethanol - Industrial World Perspectives', Renewable Energy World, May-June 2000. 'http://www.jxj.com/magsandj/rew/2000_03/bioethanol.html').
[108] (Ref. http:www.toyota.co.jp/Irweb/invest_rel/advertorial/2003318/part1/).
[109] (Ref. John Lippert, 'Toyota plans all gas-electric vehicles by 2012', Bloomberg News, October 25, 2002, quoting Masatami Takimoto, Managing Director for engine engineering. http://www.auto.com/industry/iwird25_20021025.htm).
[110] (Ref. Kansas City Star, 'California Air Rules Key in Hybrid, Fuel Cell Debate', February 28, 2003. http://evworld.com/databases/shownews.cfm?pageid=news280203-03.cfm.html).
[111] (Ref. U. Bossel et al, 'The Future of the Hydrogen Economy: Bright or Bleak ?', 15 April 2003, p 29. http://www.efcf.com/reports).
[112] (Ref. 'Hydrogen's Future Up in the Air', 2003-06-12. http://www.wired.com/news/autotech//0,2554,59220,00.html).
[113] (Ref. Mark Gainsborough, 'Sustainable Mobility Project, Workstream 3 - Fuels', September 2002, Slide 10. '18slide.pdf').
[114] (Ref. D.W. Keith and A.E. Farrell, 'Rethinking Hydrogen Cars', Science, Vol. 301, 18 July 2003, p 315).
[115] (Ref. CARB, 'Proposed Amendments to the Zero Emission Vehicle Regulation, March 27, 2003, April 24, 2003', Slide 21. 'staff.pdf').
[116] (Ref. 'Honda's CEO on Fuel Cells' Future', Business Week, December 16, 2002. http://evworld.com/databases/shownews.cfm?pageid=news161202-04.html).
[117] (Ref. http://news.yahoo.com/news?tmpl=story2&cid=1540&u=/afp/200XXX, 2003-06-14).
[118] (Ref. 'Fuel cell R & D is far from easy street', EE Times, May 22, 2003. http://www.eetimes.com/story/OEG20030522S0017).
[119] (Ref. D.W. Keith and A.E. Farrell, 'Rethinking Hydrogen Cars', Science, Vol. 301, 18 July 2003, p 315).