# Cars beyond Otto's Internal Combustion Engines

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**Road transportation as an important requirement of modern society is presently faced with restrictions in mainly two respects, namely the ever tightening emission legislation as well as the availability of petroleum fuels, and as a consequence the fuel cost. But in any review of power sources for future road transport vehicles, the performance of the existing internal combustion engine is likely to be the yardstick against which other power sources will be compared. The power sources most likely to provide favourable comparison are those, which can display comparable range and speed, long and reliable life and manufactured at a cost comparable to petrol engine. A vehicle which fails in any of these requirements is unlikely to achieve anything but a niche market share. This article is an appraisal of a variety of proposed electrochemical systems, viz. rechargeable batteries, fuel cells and supercapacitors, for an electric car. It is surmised that a viable electric car could be powered with a fuel cell to provide power for cruising and climbing coupled in parallel with a supercapacitor/battery bank to deliver additional short-term burst-power during acceleration.**

## 1. Introduction

Deteriorating urban air-quality, growing dependence on insecure energy sources and global warming are forcing a re-examination of petroleum-fueled Otto's[1] internal combustion engine vehicles (ICEVs) as the basis for road transportation throughout the world. Although modern cars emit far less toxic pollutants comprising hydrocarbons, nitrogen oxides, carbon monoxide and particulates, their increasing number is resulting in growing insistence to further reduce automobile pollution . At

[1] The Otto engine is a four-stroke internal-combustion engine invented by Nikolaus Otto in 1876. In the ideal Otto cycle, on which it is based, combustion takes place at constant volume. In a diesel engine, cycle combustion takes place at constant pressure.

present, motor vehicles account for about one-half of the total hydrocarbon and nitrogen oxide pollution which combine to form ground-level ozone, commonly known as smog, that chokes many of the major urban conurbations in the world. This has brought in emission legislation, particularly in the light of the Kyoto Protocol [1], requiring the induction of zero-emission vehicles (ZEVs). This had been thought to mean battery-powered cars. But, the battery-powered cars are found to be doubtful starters [2, 3]. Furthermore, batteries need electricity, which would be generated by burning coal to $CO_2$ and $SO_2$. By contrast, the use of fuel cells with on-board reforming of a fossil fuel to produce hydrogen is both ecologically and scientifically superior [4]. For example, the conversion of methanol to hydrogen for producing electricity in a fuel cell will help reducing the production of $CO_2$ gas by about 33% and there will be virtually no other polluting gases.

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This article estimates the power and energy requirements of a modern car and examines the feasibility of various available electric automobile power sources for realizing a viable electric drive-system.

## 2. Power and Energy Estimates for an Electric Car

In order to properly assess the use of the electrochemical energy conversion and storage systems, viz. storage batteries, supercapacitors and fuel cells, to power electric vehicles, it is mandatory to quantitatively estimate the power and energy required for propelling a modern car. Neglecting relatively minor losses due to road camber and curvature, the power required at the drive wheel ($P_{\text{traction}}$) may be expressed as [5],

$$P_{\text{traction}} = P_{\text{grade}} + P_{\text{accel}} + P_{\text{tires}} + P_{\text{aero}}, \qquad (1)$$

where $P_{\text{grade}}$ is the power required for the gradient, $P_{\text{accel}}$ is the power required for acceleration, $P_{\text{tires}}$ is the rolling resistance power consumed by the tires, and $P_{\text{aero}}$ is the power consumed by the aerodynamic drag.

The first two terms in (1) describe the rates of change of potential (PE) and kinetic (KE) energies associated during climbing and acceleration, respectively. The power required for these actions may be estimated from the Newtonian mechanics as follows.

$$P_{\mathrm{grade}} = \mathrm{d(PE)/d}t = Mgv\sin q \qquad (2)$$

and

$$P_{\mathrm{accel}} = \mathrm{d(KE)/d}t = d(1/2\,Mv^2)/\mathrm{d}t = Mav\,, \qquad (3)$$

where $M$ is the mass of the car, $v$ is its velocity, $a$ is its acceleration, and $\tan q$ is the gradient. The potential and kinetic energies acquired by the car as a result of climbing and acceleration represent reversibly stored energies and, in principle, may be recovered by appropriate regenerative methods wherein the mechanical energy is converted and stored as electrical energy. The last two terms in (1) describe the power, which is required to overcome tire friction and aerodynamic drag that are irreversibly lost, mainly as heat and noise and cannot be recovered. The power required here may be estimated from the following empirical relations.

The potential and kinetic energies acquired by the car as a result of climbing and acceleration represent reversibly stored energies and, in principle, may be recovered by appropriate regenerative methods wherein the mechanical energy is converted and stored as electrical energy.

$$P_{\mathrm{tires}} = C_{\mathrm{t}}Mgv \qquad (4)$$

and

$$P_{\mathrm{aero}} = 0.5\,dC_{\mathrm{a}}A(v+w)^2\,v, \qquad (5)$$

where $C_{\mathrm{t}}$ and $C_{\mathrm{a}}$ are dimensionless tire friction and aerodynamic drag coefficients, respectively, $d$ is the air density, $w$ is the headwind velocity, $g$ is the gravitational acceleration, and $A$ is the frontal cross-sectional area of the car.

From the parameters associated with a typical modern medium-size car, viz. $M = 1400$ kg, $A = 2.2\mathrm{m}^2$, $C_{\mathrm{t}} = 0.01$, $C_{\mathrm{a}} = 0.3$, $d = 1.17\ \mathrm{kg/m}^3$, its power requirements may be estimated from (2)-(5). For the irreversible losses, (4) and (5) show that while $P_{\mathrm{tires}}$ is linearly dependent on velocity, $P_{\mathrm{aero}}$ varies as the third power

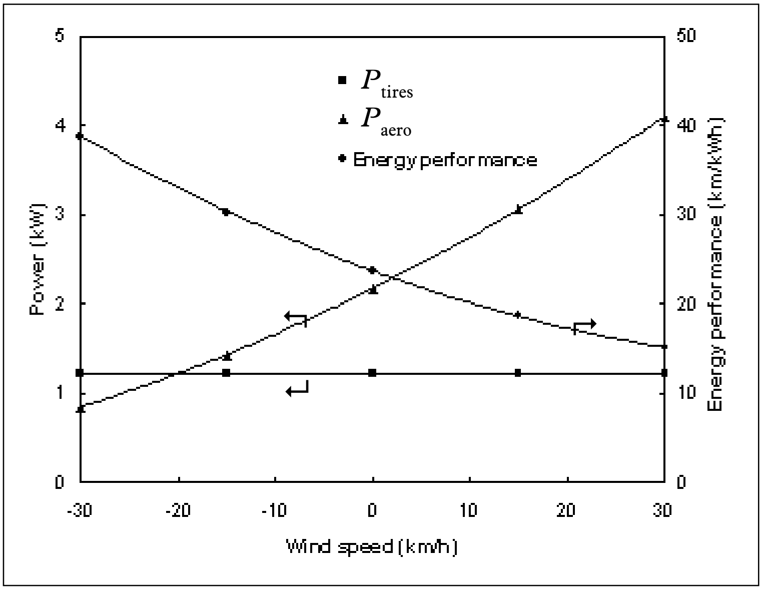

***Figure 1. Energy performance and power requirements of the car as a function of wind speed at vehicle speed of 80 km/h.***

of velocity and although negligible at low velocities, the latter becomes the dominant irreversible loss at high speed. As an example, for these parameters, for a car travelling at about 50 km/h, tire friction is twice the aerodynamic drag and together amount to about 3 kW. At 100 km/h highway cruising, aerodynamic drag increases considerably to over twice the tire friction, increasing the total power requirement to about 12 kW. It is noteworthy that for both these estimates, the wind speed ($w$) has been taken to be zero for the sake of simplicity (see *Box* 1). But, in practice the effect of wind speed on the performance of the car could be quite substantial as shown in *Figure* 1. Taking the example of a hill with a substantial 10% gradient, climbing at 80 km/h requires about 38 kW, including tire friction and aerodynamic drag (see *Box* 1). Acceleration is more demanding, particularly at high velocities. For example, acceleration at 5 km/h/s requires 30 kW at 50 km/h and increases to 66 kW at 100 km/h (see *Box* 1).

The above estimates are for the power supplied to the wheel of the car and do not include the losses incurred in delivering that power to the wheels. At this time in the development of electric-traction systems, a precise estimate of losses is difficult to obtain

**Box 1. Appendix**

(a) *Estimation of* $P_{\text{tires}}$ *at vehicle speed (v) of* 50 *and* 100 km/h.

At $v$ = 50 km/h: $P_{\text{tires}} = 0.01 \times 1400 \times 9.8 \times 50 \times 10^3/3600$ W
$= 1.9$ kW.

At $v$ = 100 km/h: $P_{\text{tires}} = 0.01 \times 1400 \times 9.8 \times 100 \times 10^3/3600$ W
$= 3.81$ kW .

(b) *Estimation of* $P_{\text{aero}}$ *at vehicle speed (v) of* 50 *and* 100 km/h.

In these estimates the wind velocity ($w$) has been taken to be zero.

At $v$ = 50 km/h: $P_{\text{aero}} = 0.5 \times 1.17 \times 0.3 \times 2.2 \times (50)^3 \times (10^3)^3/(3600)^3$ W
$= 1.03$ kW.

At $v$ = 100 km/h: $P_{\text{aero}} = 0.5 \times 1.17 \times 0.3 \times 2.2 \times (100)^3 \times (10^3)^3/(3600)^3$ W
$= 8.27$ kW.

(c) *Estimation of* $P_{\text{grade}}$ *at* 10% *gradient and* $v$ = 80 km/h.

$P_{\text{grade}} = 1400 \times 9.8 \times 80 \times 10^3 \times 0.1/3600$ W
$= 30.49$ kW.

(d) *Estimation of* $P_{\text{accel}}$ *at* $v$ = 50 *and* 100 km/h *with an acceleration of* 5 km/h/s.

At $v$ = 50 km/h: $P_{\text{accel}} = 1400 \times 5 \times 50 \times (10^3)^2/(3600)^2$ W
$= 27$ kW.

At $v$ = 100 km/h: $P_{\text{accel}} = 1400 \times 5 \times 100 \times (10^3)^2/(3600)^2$ W
$= 54$ kW.

but anecdotal information suggests that the efficiency of the power conditioning electronics together with the electrical and mechanical drive-train ($e_{\text{drive}}$) is about 0.85. Additional power ($P_{\text{access}}$) for the accessories like radio, lights, steering and air-conditioning, etc., is likely to add about 5 kW to the total power demand of the car.

In this way, the instantaneous total power required from the electric power-system ($P_{\text{total}}$) will be given by

$$P_{\text{total}} = P_{\text{traction}} / e_{\text{drive}} + P_{\text{access}} \,. \qquad (6)$$

An analysis of this kind indicates that the power plant of a modern car must be capable of delivering about 50 kW of sustained power for accessories and hill climbing, with burst-power requirement for a few tens of seconds to about 80 kW during acceleration. For a car with these performance characteristics, this sets the upper power limit required, but in common usage rarely exceeds 15 kW while cruising.

Equations (2) – (5) show that with the exception of aerodynamic losses, the power requirements scale with the mass of the car. While new light-weight materials and construction methods, together with design innovations to minimize aerodynamic drag may be able to reduce the power and energy requirements of the car, gains in excess of about 25% will be difficult to realize within an acceptable cost regime.

The energy consumed by a car is simply the time integral of the traction and accessory power plus that consumed by the power plant at idle ($E_{\text{idle}}$). Accordingly,

$$E_{\text{total}} = \int P_{\text{total}}\,\mathrm{d}t + E_{\text{idle}}\,. \tag{7}$$

$E_{\text{total}}$ depends on the nature of the drive cycle the car is required to perform. Several estimates have been made for selection of acceleration-climb-cruise-idle sequences designed to simulate common driving practices. As with the power requirements of the car, $E_{\text{total}}$ is very dependent on car mass. For the car parameters listed above, this may be expected to be near 200 Wh/km.[2]

***Table 1. Properties of diesel fuel and gasoline.***

| Physical properties | Diesel | Gasoline |
|---|---|---|
| Molecular wt. ( – ) | 208 | 99 |
| Density @ 20° C (kg/l) | 0.84 | 0.74 |
| Carbon content (% mass) | 86.1 | 84.9 |
| Oxygen (% mass) | 0 | 0 |
| Exhaust water (g/Kg) | 28.6 | 30.3 |
| Exhaust $CO_2$ (g/Kg) | 74.2 | 73.3 |
| Lower calorific value (MJ/kg) | 42.8 | 43.9 |
| Cetane number ( – ) | ~50 | ~8 |

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[2] Taking the heating value of gasoline as 32.49MJ/l (see *Table* 1), a heating value of only 6.5 MJ/l will be achievable with an internal combustion engine of near 20% well-to-wheel efficiency. This is about 1.82 kW/l of the gasoline and considering the average drive range of the car as about 10 km/l, it would amount to 182 Wh/km. The heating value for the diesel fuel is 35.95 MJ/l (see *Table* 1). Accordingly, the estimated $E_{\text{total}}$ will be 201 Wh/km with the diesel-driven cars, which have well-to-wheel efficiency of about 30% and a drive range of ~15 km/l.

| Cell type | Nominal Voltage (V) | Specific Energy (Wh/kg) | Energy Density (Wh/I) | Specific Power (W/kg) | Power density (W/I) | Self Discharge (%/month) | Cycle life |
|---|---|---|---|---|---|---|---|
| Lead-acid | 2.0 | 35 | 70 | ~200 | ~400 | 4-8 | 250-500 |
| Lithium-ion | 3.6 | 115 | 260 | 20-250 | 400-500 | 5-10 | 500-1000 |
| Lithium-polymer | 3.0 | 100-200 | 150-350 | >200 | >350 | ~1 | 200-1000 |
| Nickel-cadmium | 1.2 | 40-60 | 60-100 | 140-220 | 220-350 | 10-20 | 300-700 |
| Nickel-metal hydride | 1.2 | 60 | 220 | 130 | 475 | 30 | 300-500 |
| Zinc-air | 1.2 | 146 | 204 | 150 | 190 | ~5 | ~200 |
| Zebra | 2.6 | 100 | 160 | 150 | 250 | ~1 | ~1000 |

***Table 2. A comparison of the most promising storage batteries for electric cars.***

## 3. An Appraisal of Electric Automobile Power Sources

### 3.1 *Background*

With the background of storage batteries, fuel cells and supercapacitors given in the earlier articles (*Resonance* – July and August issues), we will now picture the perspective of these options for electric cars. The power and energy density parameters of the storage batteries discussed in Part 1 are given in *Table* 2. From the cost perspective, lead-acid batteries appear to be the most attractive, but with an energy density of only about 35 Wh/kg, almost 6 kg of battery is required to drive a car for 1 km. Coupled with its relatively slow recharge characteristics, it is immediately apparent that the lead-acid battery, in spite of its technical maturity and low-cost, is an unacceptable option. Indeed, the failure of General Motor EV1 to find consumer acceptance may, at least in part, be linked to its dependence on lead-acid batteries [2]. When the high-temperature zebra batteries are rejected for their inability to offer acceptable intermittent operational performance, it is seen from *Table* 2 that the most viable battery systems are either the nickel-metal hydride or lithium secondary types. Even neglecting the high cost of these battery systems, their energy densities still require 2-2.5 kg of battery to travel 1 km. At 1kg/km, the zinc-air battery is approaching an acceptable performance, but technical difficulties in achieving a truly rechargeable system continue to frustrate their commercial implementation. It is noteworthy that the vanadium redox and zinc-bromine flow batteries have also been projected as possible contenders for vehicular traction. These batteries, however, have problems of excessive self-discharge. Besides, vanadium and bromine are highly toxic.

The relative power and energy densities of the current generation supercapacitors, storage batteries and fuel cells may be summarized in a Ragone diagram of the type shown in *Figure* 2. As discussed earlier in section 2, the overall energy demand of a modern electric car is about 200 Wh/km, in which case the power plant should be capable of delivering in excess of 500 Wh/kg for it to be within acceptable limits in relation to the energy-density range of the spark-ignition engines. It is immediately apparent that this cannot be achieved by any of the direct electric energy storage systems, namely supercapacitors or batteries, and that it is unlikely to be an achievable target for these systems within the foreseeable future. At best, storage batteries

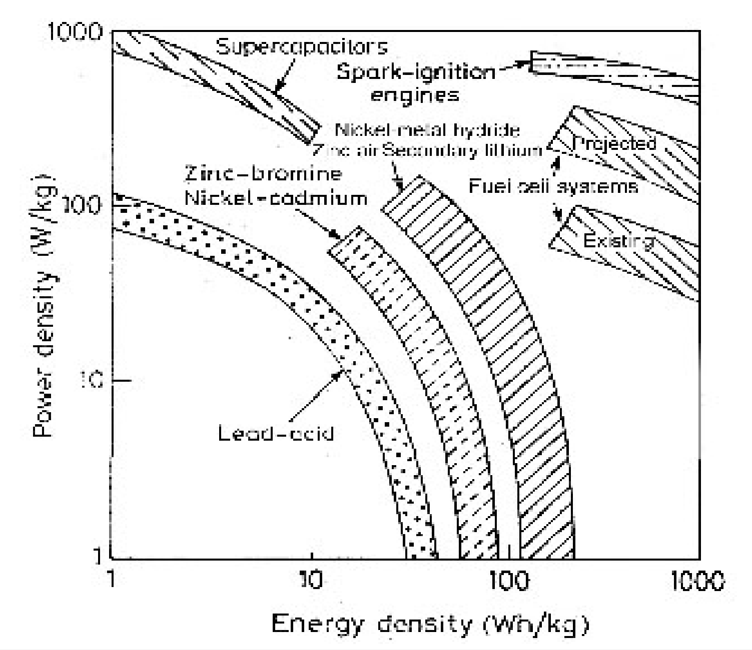

**Figure 2. A Ragone plot comparison of power and energy densities for existing supercapacitors, storage batteries, fuel cells (including reformer), and spark-ignition engines.**

and supercapacitor powered vehicles may be able to find limited niche applications in short-range commuter vehicles, especially where the relatively long recharge times can be accommodated by the pattern of vehicle usage. An interesting niche market could be in the neighbourhood electric vehicle (NEV). This is a vehicle, which is designed to provide low-speed, personal transportation in restricted areas. Examples would be university campuses, hospitals, theme parks, industrial parks, holiday resorts, residential communities and of course, citycentres. The NEVs would be restricted to speeds of 40-50 km/h. Various small electric cars with lead-acid are being designed to meet this niche market.

### 3.2 *Fuel Processor Options for Electric Cars*

For transportation, the low-operating temperature and rapid start-up characteristics, together with its robust solid-state construction give the polymer-electrolyte fuel cell (PEFC) a clear advantage for application in cars. Its energy conversion efficiency is much higher than both the Otto and Diesel versions of the internal-combustion engines. The preferred fuel for the PEFCs is hydrogen. While many strategies for providing hydrogen to PEFCs are presently being evaluated (*Figure* 3), the most acceptable proposal appears to be to generate hydrogen on-board and on-demand from liquid hydrocarbons or methanol. The technical challenge, however, lies in modifying large-scale industrial processes like steam reforming or partial-oxidation (POX) reactors to lightweight units that can fit inside the car.

At best, storage batteries and supercapacitor powered vehicles may be able to find limited niche applications in short-range commuter vehicles, especially where the relatively long recharge times can be accommodated by the pattern of vehicle usage.

The proto-type fuel cell car (NECAR-3) demonstrated by Daimler–Chrysler is based on steam reforming of methanol, which is relatively easy to process on-board and may be conveniently distributed through the existing service-station infrastructure. Meanwhile, POX reactors for processing gasoline, which is favoured by the Department of Energy (DOE) in the US, are being developed by Epyx Corporation. POX offers compact reactors, fast start-up and rapid dynamic response while steam reforming produces more hydrogen with an in-

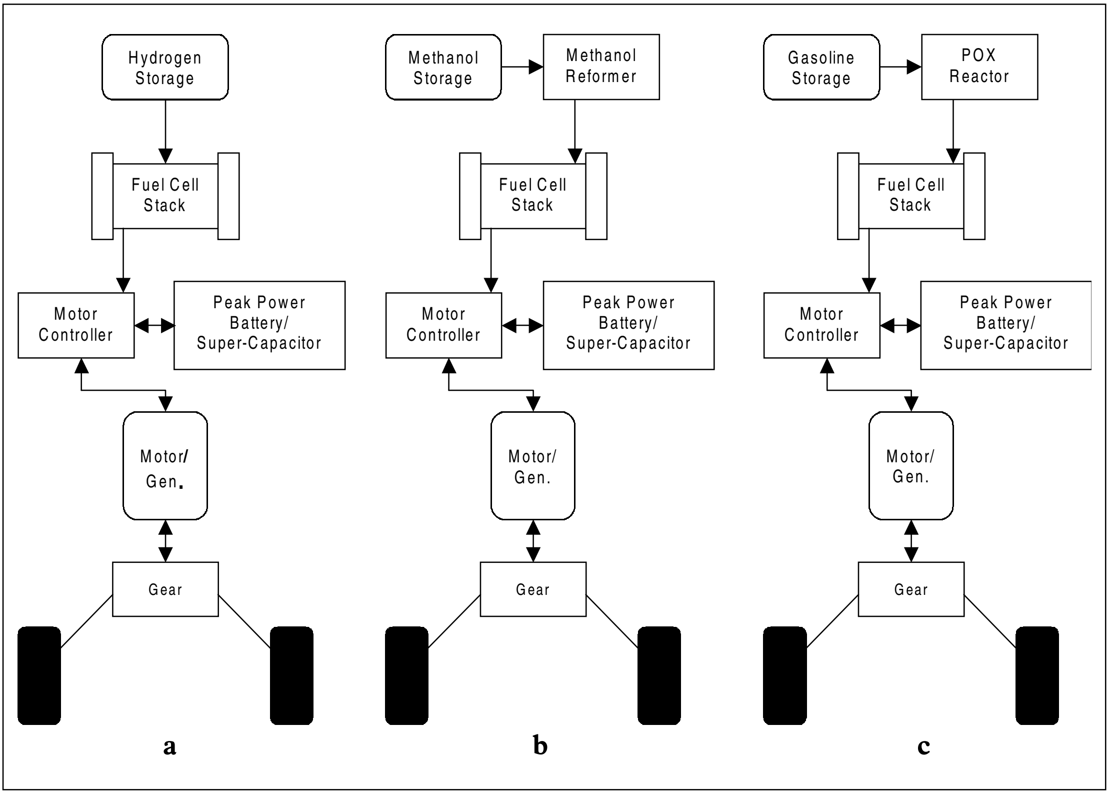

***Figure 3. Feasible fuel cell system configurations: (a) with direct hydrogen fuel, (b) with methanol reformer, and (c) with a partial oxidation (POX) reactor.***

creased efficiency. Johnson–Matthey in the UK have developed a methanol processor called the HotSpot which uses the heat produced by the POX process to drive the steam reforming reaction. This compact system ensures fast start-up and optimum fuel efficiency. But the hydrogen produced by steam reforming and POX of methanol contains carbon dioxide (~ 20%) and traces of carbon mon-oxide (~2%). At the operating temperatures of the PEFCs, carbon monoxide even at 0.01% is sufficient to poison the platinum catalyst at the anode. Two strategies to circumvent this problem are under way. Either carbon monoxide must be removed from the hydrogen stream in a separate process or new carbon monoxide tolerant catalysts need to be developed for deployment at the anode. Production of relatively pure hydrogen from a wide range of commercially available fuels is unargu-ably the ultimate step in the commercialization of polymer-electrolyte fuel cell cars. North-West

Power Systems have recently achieved a milestone in this direction by acheiving up to 50 litre per minute of pure hydrogen from a methanol fuel processor, as also a successful demonstration of pure hydrogen production using propane and ethanol; with modification, the fuel processor can operate on gaseous feedstock such as methane (natural gas). This multi-fuel processor combines three functions comprising catalytic steam reforming, heat generation by low-pressure combination of a fuel gas and hydrogen generation.

Geographically petroleum is not widely distributed, rendering countries with the largest reserves disproportionate economic and political sway.

An elegant solution to the problems associated with the need for gaseous hydrogen fuel, lies in operating the PEFCs directly with a liquid fuel. Much consideration is therefore being given to PEFCs that run on air plus a mixture of methanol and water. The main technological challenges here are to develop better anode catalysts to overcome efficiency losses at the anode and to improve the membrane electrolyte, as also to find cathode catalysts to prevent its methanol poisoning. A solid-polymer-electrolyte direct methanol fuel cell (SPE-DMFC) would be about as efficient as a conventional methanol reformer/PEFC system. But, since the SPE-DMFCs do not involve any auxiliary units, the development of a commercially feasible SPE-DMFC would be simpler than a PEFC unit, in both its construction and operation. Indeed, SPE-DMFCs are widely regarded as the 'holy grail' of fuel cell technologies. The operational difference between a PEFC and a SPE-DMFC electric car is shown in *Figure* 4. Ironically, for the present, oil companies world over are favouring hydrogen from gasoline as the fuel for the future fuel-cell cars, and the political will to project methanol as a fuel is wanting. However, geographically petroleum is not widely distributed, rendering countries with the largest reserves disproportionate economic and political sway.

At present, the PEFC is emerging as the most viable electric option for the cars. Since the energy density of the PEFC power plant is akin to that of the present-day spark-ignition engines (*Figure* 2), comparable driving ranges may be expected. But, the power density of present PEFC systems tends to be lesser than

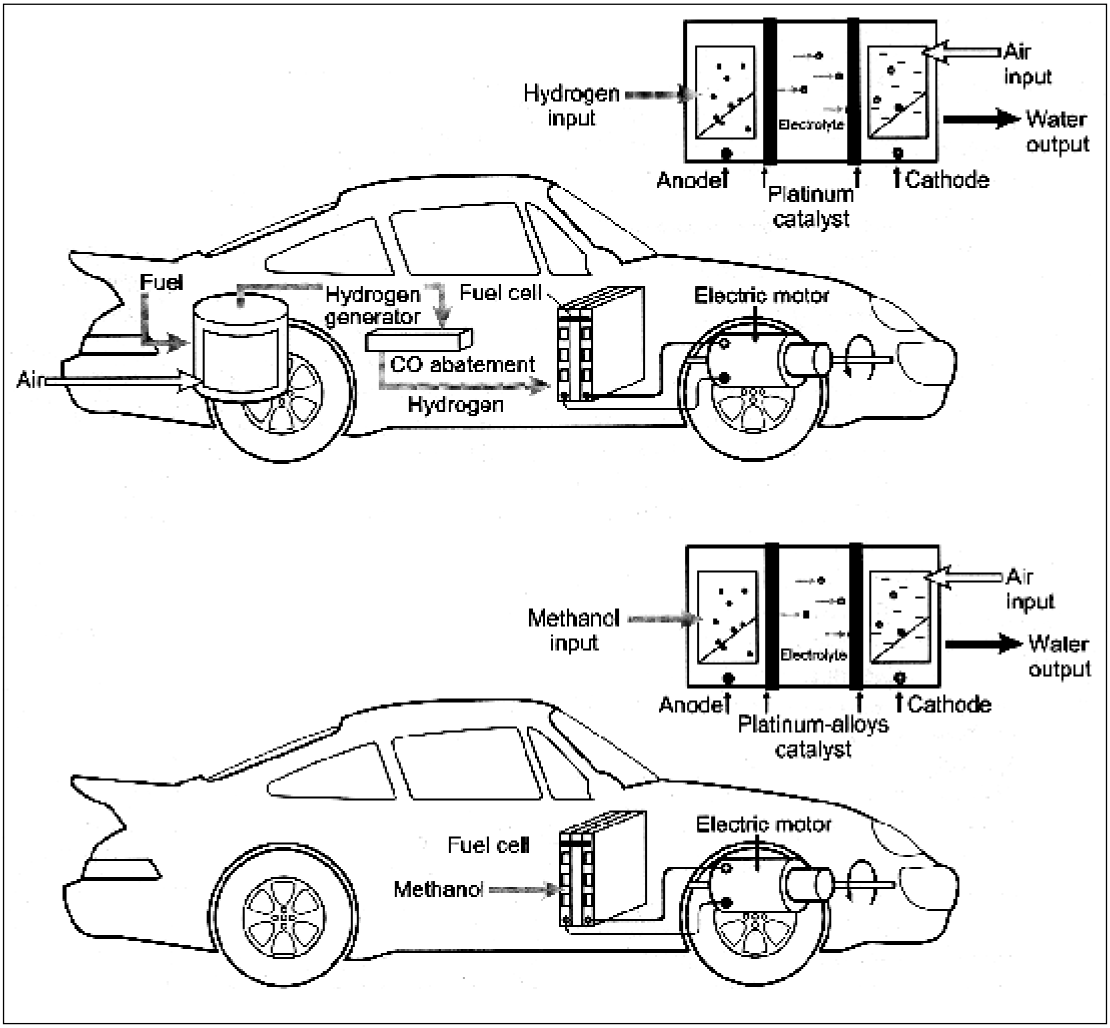

***Figure 4. Operational differences between: (a) a fuel cell electric car with onboard reformer for hydrogen generation, and (b) a fuel cell electric car with direct methanol feed.***

that of the spark-ignition engines. Although, the 80 kW of power needed to provide the acceleration could be supplied by an appropriately-sized PEFC alone, this will probably make the first generation systems excessively large and heavy. Additionally, the high cost of newly developed fuel cells will persuade the car makers to use the smallest cells that will provide the required base power needs of about 50 kW.

### *3.2 Technology Alternatives for Electric Cars*

An acceptable compromise could be achieved with a supplementary parallel electric storage system using either high power-density supercapacitors or, less likely, storage batteries to provide the short-duration acceleration. This electric storage system could also be used to regeneratively recover the energy, which would be otherwise lost during braking. Since energy density is less important than power density for the acceleration of a car, supercapacitors would appear to be a superior alternative to any of the present storage battery options. But with the development of electric propulsion systems still in its infancy, the final mixing and matching of the electric power options will depend as much on new and refined technological developments as it will on consumer demands. It is however projected to increase the power densities of the PEFC systems to about 300 W/kg by 2004 and significant progress has already being made towards this goal [6]. Such an achievement will help cutting down both the size and weight of the PEFC systems appreciably, and, in future, the entire power requirement of the car could be met with a compact fuel cell system itself. But, even then, future cars would preferably keep an appropriately sized battery or supercapacitor unit to regeneratively recover the energy during braking which could be used on demand.

With the development of electric propulsion systems still in its infancy, the final mixing and matching of the electric power options will depend as much on new and refined technological developments as it will on consumer demands.

In a clear demonstration of its commitment to have fuel-cell cars in series production by 2004, Daimler–Chrysler have recently unveiled its NECAR-4 version. Its fuel cell power output has been increased by 40%, giving it a top speed of 145 km/h, acceleration to 48 km/h in 6 seconds, and a range of up to 450 km, which is comparable to conventional ICEVs. Like its predecessor NECAR-3, the new car is based on a Mercedes-Benz A-Class sub-compact car, which has a sandwich floor construction within which the system can be installed. For the first time, the complete PEFC system is mounted in the vehicle floor, allowing room for up to five passengers and cargo space. It is powered by liquid hydrogen stored in a cryogenic cylinder that takes up a part of the trunk. The engine was developed by Daimler Benz-Ballard (dbb) Fuel Cell Engines GmbH, while the vehicle uses an electric drive train from Ecostar Electric Drive Systems, a joint venture between Daimler–Chrysler, Ford and Ballard, which supplied the fuel cell stacks. There was some surprise at the choice of hydrogen as fuel in place of methanol, which powered NECAR-3. But Daimler–Chrysler is already working on an advanced fuel cell system, which will use methanol as the fuel. According to Daimler–Chrysler, for the near term, methanol is not only the clear choice to introduce fuel cell vehicles for consumer use in 2004, but it has long-term environmental benefits because methanol could be produced renewably. Daimler–Chrysler believes that the most challenging problems have been solved; the new race is to make them affordable. This is because to achieve widespread acceptance in coming years, the electric cars must have a clear economic advantage over ICEVs.

Today, we stand at the threshold of a new era in alternative vehicular propulsion. Electric vehicles hold the promise of allowing us to continue to enjoy the freedom and mobility that we have become accustomed to and at the same time to do so in a much more fuel efficient, environmentally clean, and sustainable manner.

## 4. Conclusions

Global economic, environmental and political issues are pushing car manufacturers to build electric power systems as an alternative to the current ICEVs. It is demonstrated that a viable electric car could be operated with a 50 kW PEFC system to provide power for cruising and climbing, coupled in parallel with a 30 kW supercapacitor and/or battery bank to supply the additional short-term burst power during acceleration. Recently, a major alliance between Daimler Benz, Ford and Ballard has been formed to realize and commercialize electric cars who are committed to have fuel cell cars in series production by 2004.

## Acknowledgements

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