Electric vehicle drive systems

M. Appleyard
Lucas Automotive Ltd., Solihull, B90 4JJ (UK)

Abstract

New legislation in the State of California requires that 2% of vehicles sold there from 1998 will be 'zero-emitting'. This provides a unique market opportunity for developers of electric vehicles but substantial improvements in the technology are probably required if it is to be successfully exploited. There are around a dozen types of battery that are potentially relevant to road vehicles but, at the present, lead/acid and sodium–sulphur come closest to combining acceptable performance, life and cost. To develop an efficient, lightweight electric motor system requires up-to-date techniques of magnetics design, and the latest power-electronic and microprocessor control methods. Brushless machines, coupled with solid-state inverters, offer the most economical solution for mass production, even though their development costs are higher than for direct-current commutator machines. Fitted to a small car, even the highest energy-density batteries will only provide around 200 km average range before recharging. Therefore, some form of supplementary on-board power generation will probably be needed to secure widespread acceptance by the driving public. Engine-driven generators of quite low power can achieve useful increases in urban range but will fail to qualify as 'zero-emitting'. On the other hand, if the same function could be economically performed by a small fuel-cell using hydrogen derived from a methanol reformer, then most of the flexibility provided by conventional vehicles would be retained. The market prospects for electric cars would then be greatly enhanced and their dependence on very advanced battery technology would be reduced.

Introduction

With the rapid growth in traffic density, there is an urgent requirement both to reduce our dependency on the non-renewable supplies of crude oil and also to reduce air pollution. So far, though, it has proved difficult to arrive at alternative fuels and power plants which have sufficient benefits and low enough costs to be acceptable in the market place.

The vehicle industry has therefore focussed most of its efforts towards improving the efficiency and the emissions of existing gasoline and diesel engines. Because such developments tend to add to the initial cost of the product, their implementation has largely been due to government action. So far, the legislators have been content to set standards which, while stretching the capabilities of known technology, have stopped short of forcing very radical changes upon the industry.

However, recent proposals by the Californian Air Resources Board (CARB), clearly move beyond this by stipulating that 'zero-emitting vehicles' (ZEVs) constitute a minimum percentage of annual sales from 1998 onwards. The 'zero' definition applies

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to the tailpipe emissions of hydrocarbons (HC), carbon monoxide (CO) and nitrogen oxides (NO_x).

The CARB regulations also specify rising sales percentages for vehicles with intermediate levels of emissions such as 'low-emitting vehicles' (LEVs) and 'ultra low-emitting vehicles' (ULEVs). The overall schedule is shown in Table 1. The 'ZEV' element of this legislation is extremely significant for electric vehicles since they represent the only realistic means for eliminating tailpipe pollutants. Consequently, several leading vehicle manufacturers have initiated EV product programmes in order to protect their market position in California. They are also mindful of moves in other US States to adopt similar standards.

There have been several previous periods of heightened interest in EVs, mainly due to concerns about oil supplies. However, in spite of a certain amount of technical progress, three main areas of difficulty persist, namely:

- the high cost, the maintenance problems, the limited life and the low energy density of batteries
- the limited operating range available before needing to recharge the battery
- the high cost and complexity of adequately efficient motor/controller systems

Because of these, most of the more successful earlier demonstration projects have been aimed at local goods delivery and public transport applications, where operating distances are predictable and trained staff are employed to drive and maintain the equipment. However, if the chief objective is to significantly reduce air pollution, then the private car must also be targetted and electric traction componentry must be developed to the point where it is suitable for large numbers of individual users.

TABLE 1

California clean air requirements

			Transitional low-emission vehicles	Low-emission vehicles	Ultra-low emission vehicles	Zero-emission vehicles
HC (gal./m.)	0.39	0.25	0.125	0.075	0.040	0
CO (gal./m.)	7.0	3.4	3.4	3.4	1.7	0
NO_x (gal./m.)	0.4	0.4	0.4	0.2	0.2	0
Model year	% of automakers' fleets					
2003				75	15	10
2002				85	10	5
2001				90	5	5
2000				96	2	2
1999		23		73	2	2
1998		48		48	2	2
1997		73		25	2	
1996		80	20			
1995		85	15			
1994	10	80	10			
1993	60	40				
1992	100					
1991	100					

Batteries

There are many combinations of chemical elements or compounds which can be used to construct a battery. However, their application to road vehicles raises a number of practical requirements which eliminate all but a few. The key considerations are:

energy: weight and energy: volume
power: weight and power: volume
charge/discharge cycle efficiency
initial cost and residual value
charge/discharge cycle life
maintenance requirements
operating temperature
reliability
safety

The most fully researched systems are listed in Table 2, together with some of their more important characteristics. The comments that follow also highlight their respective key strengths and weaknesses.

Lead/acid

The lead/acid cell is well established and there is a developed infrastructure for recycling scrap. The active materials are heavy and their utilization within the cell is poor. There is an underlying design trade-off between energy density and cycle life. The latter can be improved if tubular-style positive plates are used instead of the more common flat type, although these increase the cost. In spite of this, lead/acid batteries are cheaper than most others. The sealed versions do not require regular topping-up or gas management, which makes them much more suitable for the private user. However, at the present state of the art, the cycle life of sealed cells is lower than for non-sealed for a given target energy density.

TABLE 2

Characteristics of traction cells

	Energy/ weight (W h/kg)	Power/ weight (W/kg)	Volts per cell	Cycle life (nos.)	Temperature range (°C)	Cost/ kW h ($)
Lead/acid (non-sealed)	40	80	2.05	1000	0–40	80
Lead/acid (sealed)	35	70	2.05	1000	0–40	100
Nickel–iron	55	100	1.37	1500+	0–40	200
Nickel–cadmium	44	200	1.30	1500+	0–40	500
Nickel–zinc	66	150	1.71	300+	0–40	250
Lithium–iron sulfide	100	250	1.60	600+	450	150
Lithium–polymer-electrolyte	85	20	2.00	100+	100	TBA
Sodium–sulfur	120	150	2.08	2000+	350	100
Sodium–nickel chloride	125	150	2.59	300+	250	130
Zinc–air	100	50	1.65	300+	60	TBA
Zinc–bromine	60	220	1.81	50+	60	75
Zinc–chlorine	90	220	2.12	200+	0–40	TBA
Iron–air	80	200	1.28	200	40	90

Where the priority is to have high short-term power delivery, rather than deep-discharge performance, then the sealed cell is already well proven in engine-starting applications. This makes it potentially interesting for hybrids, especially as it is already highly mass produced in this form. For extreme power densities, so called 'bipolar' lead/acid cells are possible which, although not offering particularly good deep-cycle life, could also be significant in hybrid systems.

Nickel–iron

These can have good deep-cycle life, combined with energy densities around 50% greater than lead/acid cells. However, this is probably not a sufficient improvement to justify the key drawbacks of poor low-temperature performance, relatively high self-discharging rate, poor energy-cycle efficiency and high rates of water loss. The relatively low cell voltage increases the number of units required to build a battery of a given overall voltage. Because of this, and also because it contains nickel, it is an inherently expensive system.

Nickel–cadium

The nickel–cadium cell is superior to nickel–iron in respect of cycle efficiency, self-discharge and water consumption, but suffers from even higher costs due to the cadium. It also brings into play the problems of cadmium toxicity.

Nickel–zinc

The nickel–zinc battery provides similar energy density to nickel–iron but with a higher voltage per cell and improved power capability. To date, though, life has been limited to a few hundred cycles, mainly because the zinc electrode is prone to shape change in the form of dendritic growths. (This is a feature common to other cells using zinc electrodes.) Also, separator stability is a problem. In common with other nickel-based systems, costs are high.

Lithium–iron sulfide

This is a high-temperature system (450 °C), requiring substantial heat insulation and a thermal management system. Liquid lithium is very corrosive and this is reflected in the cost of the material used for the separator and other cell components. Retention of the lithium within the porous current collectors is a problem after extensive cycling. The battery may be vulnerable to damage by overcharge and overdischarge.

Lithium–polymer electrolyte

This cell operates most effectively at a little over normal ambient temperatures but, at present, offers only low power density. Energy density, though, is quite good as is the cell voltage, and the materials used are in abundant supply. One of its attractions is its construction which does not require the containment of liquids. This enables cells to be constructed in a wide variety of shapes to suit vehicle packaging constraints. Work is continuing to improve the stability and the low-temperature conductivity of the polymer electrolyte.

Sodium–sulfur

The most highly developed of the 'new' traction cells, sodium–sulfur, provides around three times the energy density of the best lead/acid batteries, adequate power density and a reasonable cell voltage. The basic raw materials are very abundant and cheap. The most obvious drawback is the high operating temperature (300–370 °C) which creates the need for insulation and thermal management, as well as demanding fairly high grade materials for some of the internal parts. The cells themselves are not tolerant of overvoltage or overdischarge, so cell matrix-interconnection and charge-management strategies are employed to protect them and to limit damage and capacity loss if individual units fail. These factors tend to offset the low cost of the active materials but, nevertheless, the overall cost per unit of capacity is still expected to be competitive with lead/acid.

The main economic advantage should prove to be the cycle life. Because the electrodes are liquid, their durability will not be influenced by shape change effects; therefore, several thousands of cycles are theoretically possible. Crash safety is a potential worry, but the key developers have adopted cell and battery designs which are claimed to ensure that this will not be an obstacle. As with all high-temperature batteries, a predominant issue will be whether private users will exercise the operating disciplines needed to ensure that the battery is maintained in a hot condition at all times (e.g. during long-term parking).

Sodium–nickel chloride

Seen as a possible alternative to sodium–sulfur, the sodium–nickel chloride cell has benefits in terms of a lower operating temperature, and a high cell voltage. Also, because the cells tend to fail in a short-circuit rather than open-circuit mode, there is less of a need for complex interconnections to preserve the battery's usable capacity and fewer numbers of larger capacity cells are therefore employed. These features go some way towards offsetting the high cost of the nickel. Crash safety is claimed to be less of a problem due to the use of solid reactants. Cycle life data is limited so far and the beta-alumina electrolyte is, as yet, less reliable than in the sodium–sulfur cell. A version of the battery is being investigated which uses iron in place of nickel. This lowers the cost, but also reduces the cell voltage to around 2.35 V, and reduces the energy density.

Zinc–air

The zinc–air cell can provide similar energy density to sodium–sulfur at temperatures only a little above ambient. However, the power density is lower, as are the cell volts. The chief drawbacks have been the life limitations caused by dendritic growths at the zinc electrode and the stability of the air electrode. Although the raw materials are cheap, the system is mechanically complex due to the force circulation and processing of the electrolyte.

Zinc–bromine

The zinc–bromine cell provides moderate energy density at temperatures a little above ambient and at a reasonable cell voltage. Power density is high but the cycle efficiency is poor. High cycle life has yet to be proven, with the problem of dendritic growths being a major factor. The raw materials are cheap but the cell construction is quite complex. Nevertheless, the claimed mature costs are among the lowest.

Zinc–chlorine

The zinc–chlorine cell offers improvements over zinc–bromine in most performance aspects but requires complex auxiliaries. These include circulation plumbing and refrigeration for the electrolyte during recharging. Adequate cycle lives have still to be demonstrated. The basic raw materials are cheap and lightweight.

Iron–air

Moderate energy density and high power can be achieved with this battery, albeit at low cell volts. The optimum operating temperature is a little above ambient. A thermal management system is needed, partly because of the poor cycle efficiency (only 40%). Self discharge is quite high and the stability of the air electrode is a problem. Because of the cheap raw materials, costs could be relatively low.

Motor systems

Compared with the problems posed by battery technology, those of providing a motor/controller for an electric car may seem relatively slight. However, experience of producing such equipment with similar performance and cost to a gasoline engine shows that this area, too, presents some major hurdles.

The task cannot be undertaken in isolation from the battery because, from the outset, a compromise is necessary concerning the nominal system voltage. Typically,

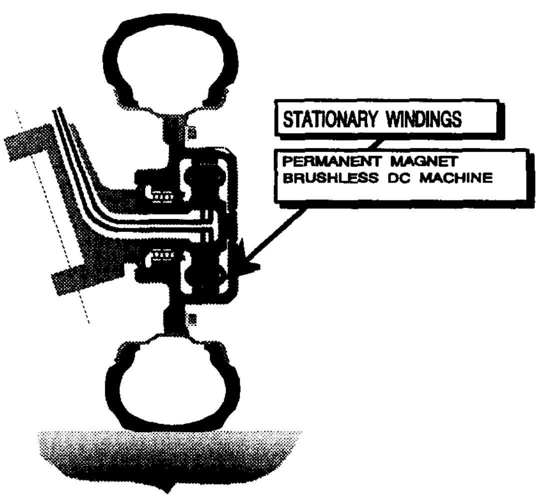

Fig. 1. Direct-drive wheel motor.

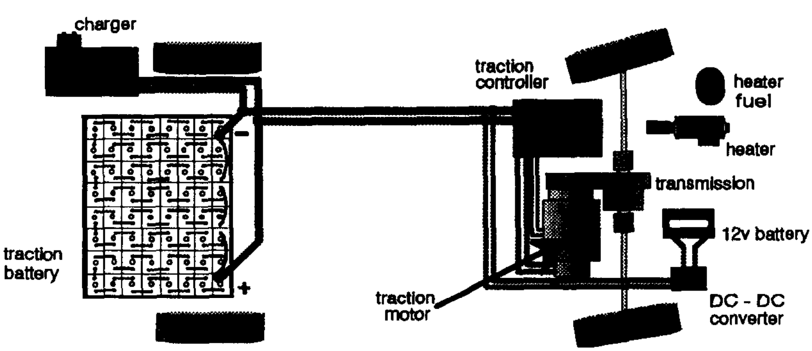

Fig. 2. Battery-electric vehicle drive system.

TABLE 3

Comparison of motor technologies

	Major strengths	Major weaknesses	Technical risk (5 = high; 0 = low)
d.c. Commutator – sep. ex.	simple control, smooth	costly motor, weight	1
d.c. Commutator – series	v. simple control, smooth	high speed power, weight, efficiency	0
a.c. Induction	low cost motor, brushless	lower efficiency, complex control	2
d.c. Brushless perm. mag.	power, size & weight, controllability	cost of magnets, field-weakening	3
Switched reluctance	v. low cost motor, efficient	noise, ripple, complex control	4
a.c. Synchronous	controllability, efficient	cost, slip rings, feedback required	5
a.c. Brushless	as d.c. brushless	as d.c. brushless	3
d.c. Axial field (pancake)	packaging? smooth	commutator, thermal managment	5

the motor/controller system has optimum cost and weight when a nominal level of a few hundred volts is chosen. However, the higher this figure, then the larger the number of individual cells that have to be constructed and connected in series. Ideally, from the battery's point of view, it would consist of a single very large cell, but a system voltage of 1.3–2.6 V is completely impractical. The constraints of vehicle packaging often require the battery to be split into small units, in any case.

Sub-division of the motor system itself is also sometimes proposed through using two or four individual motor-in-wheel units. An example of such a one is shown in Fig. 1. This gives more scope to the vehicle designer by eliminating the drive shafts and differentials. In practice the net added cost proves to be prohibitive, especially with the proliferation of the power-electronic control units. Therefore, the type of layout shown in Fig. 2 is more realistic.

There are several alternative styles of motor to consider. There are listed in Table 3, together with an indication of their strengths and weaknesses. All the machines described are capable of delivering full-power regenerative braking down to low speed, in a controlled manner. The three last machines listed in Table 3 give no clear benefits as far as EVs are concerned. However, they are included there for completeness.

The prevailing view is that the a.c. induction motor and the switched reluctance motor are the leading candidates for future EV mass production, but this does not underestimate the effort that is needed to develop the electronics to acceptable cost and reliability levels. Here again, the designers are presented with several alternative technologies. Table 4 lists the various types of solid-state switching device that can be considered for the circuits described previously, together with some key factors.

TABLE 4

Power switching devices

Thyristors	require separate circuits to turn-off current		
Gate turn-off thyristors (GTOs)	low turn-off grain, restricted to below 8 KHz		
MOS controlled thyristors (MCTs)	not yet mature and therefore still inferior to IGBT although overall losses lower		
Bipolar transistors	high losses above 2 KHz, requires complex drive circuits		
Power MOSFETs	capable of high frequency (above 20 KHz), but high on-state loss		
Insulated-gate bipolar transistors (IGBTs)	acceptable losses at 8 KHz, mature technology, good silicon utilization, simple gate drive		

The insulated-gate bipolar transistors seem set to become the most widely used in future high performance EV drives.

Performance and range

After price, the desirability of owning an electric car will most likely be judged by its performance and range and these are the very aspects which are most compromised by the existing technology. Furthermore, the way in which the chosen battery technology is implemented in order to maximize these will almost certainly affect the battery's life. This last issue should not be overlooked since the eventual cost of a replacement will be a major item and will impinge on the resale value of the vehicle. Therefore, while a number of EV developers have made impressive claims as to the performance and range of recent prototypes, one should be aware of the method of testing and the commercial viability of the particular batteries that were employed. Actual experience of producing EVs for sale to third party customers encourages a realistic view of these issues.

Performance and range estimates have been prepared for a small battery-powered saloon-style car which uses presently available cell technology and conventional vehicle building practice. A key assumption was that the weight of the battery would be limited to what could be accommodated within gross vehicle weight upgrade of 30%, relative to the gasoline powered version. Furthermore, the volume of the battery would not interfere with the main chassis components of the standard vehicle nor cause the available luggage space to be reduced to less than that of the hatchback version of the same model (all four seats being in use).

Two battery schemes were initially examined, as illustrated in Fig. 3. The first comprised seven 12 V (i.e. 6-cell) sealed tubular-plate lead/acid traction monoblocs of 105 A h nominal capacity. The second scheme involved using eleven monoblocs instead. The maximum power that could be obtained from each monobloc, down to the 50% charged condition, was specified as 2 kW. This recognized the desirability of operating the battery in a manner that would ensure a life of 1000 cycles. The power available from each monobloc, when 20% discharged (i.e. at the safe discharge limit), was 1.5 kW. Figure 4 shows acceleration curves for this vehicle when carrying 150 kg of payload, using the two respective battery types at the 50% and 20% charged condition. It clearly indicates that the performance is seriously constrained by using lead/acid traction cells.

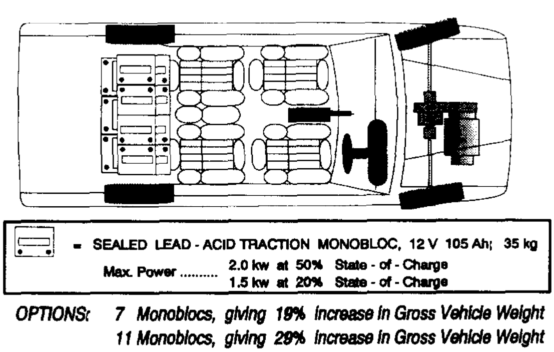

Fig. 3. Small 4-seat electric car.

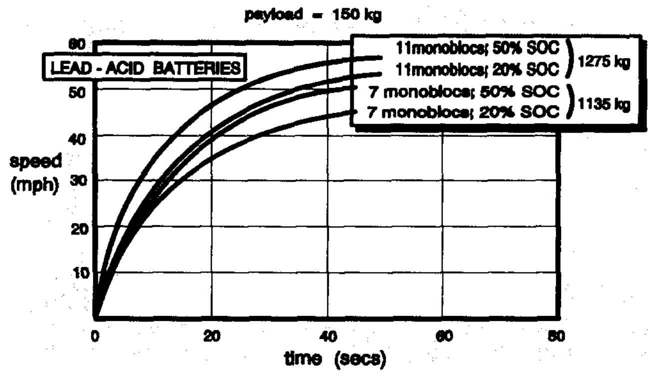

Fig. 4. Performance estimates for small 4-seat electric car.

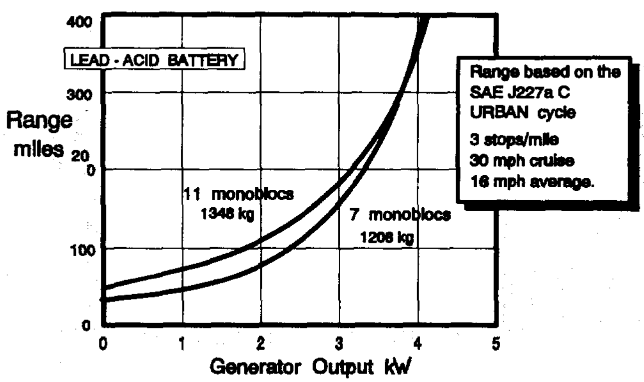

Fig. 5. Range estimates for small 4-seat series-hybrid electric car.

Hybrids

Range estimates were computed for both battery options, assuming that the vehicle was being driven in accordance with the SAE J227a C urban cycle. The effect was also examined of including an on-board engine-driven generator to create a hybrid, and the ranges were re-calculated for different continuous generator power levels. A fixed allowance was made for the extra weight of this auxiliary power unit. The results are given in Fig. 5. The zero kW values for range relate to a battery-only vehicle and highlight its limitations (30–50 miles). The improvements that can be gained from even as little as 2 or 3 kW of APU output are considerable. However, this partly reflects the low average speed and power consumption of this particular driving regime.

The constant-speed data for the 7-monobloc version given in Fig. 6 indicates how the range-enhancing effect of the APU rapidly reduces as the speeds increase. (Note, incidently, that the J227a C cycle ranges roughly equate to those for 35 m.p.h. constant speed.)

The performance curves and the urban cycle range estimates were repeated (Fig. 7) using predictions of sodium–sulfur battery performance, assuming three different states of evolution, namely the present, near-term and long-term. The acceleration obtained from the present-day sodium–sulfur cells equates with that achieved with

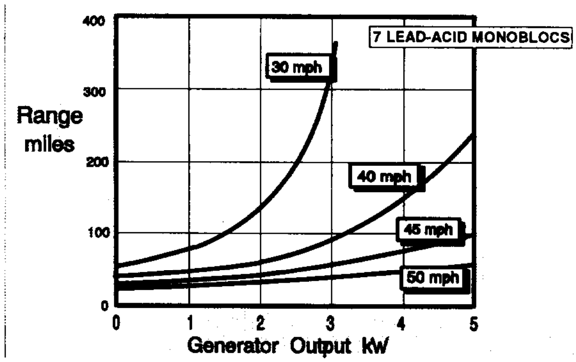

Fig. 6. Constant speed range for small 4-seat hybrid electric car.

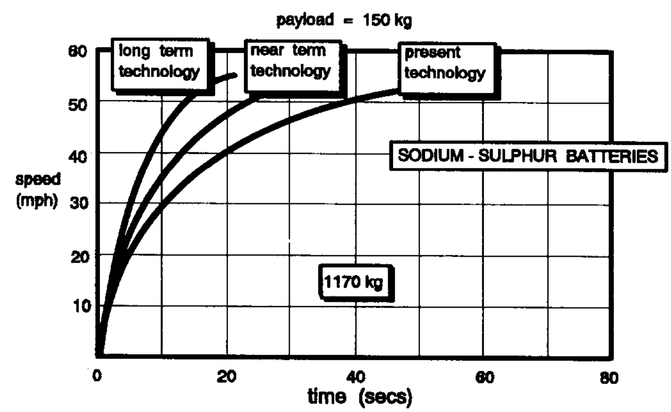

Fig. 7. Performance estimates for small 4-seat electric car.

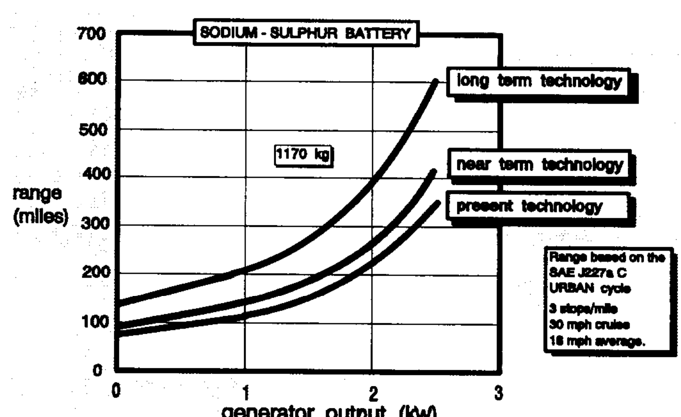

Fig. 8. Range estimates for small 4-seat series-hybrid electric car.

the 7 lead/acid monoblocs in the 50% charged condition (Fig. 4), i.e. 0–40 m.p.h. in around 20 s. The further expected improvements are clearly more promising, with the 8 s figure shown for the long-term enhancement being quite competitive with current economy cars. The range estimates of Fig. 8 follow a similar pattern, with 80 miles being expected from today's battery-only sodium–sulfur car and up to 135 miles being a possibility for the future. Once again, the effect of adding even a small APU is dramatic as far as urban driving is concerned.

Benefits of fuel-cell hybrids

To maintain 70 m.p.h. indefinitely requires 14.5 kW at the wheels, which equates to around 18 kW at the generator output. To install such a large gasoline or diesel-powered APU would create a highly ambiguous vehicle. It would compare unfavourably with its conventional counterpart as a long distance vehicle due to the extra weight of the cells and the losses in the various power conversions. It would compare unfavourably with the pure-battery vehicle as an environmentally friendly local commuting/shopping car due to the down-sizing of the battery to accommodate the APU. The chief drawback, though, in view of the nature of the new legislative pressure for EVs, is the fact that it would not qualify as a 'zero-emitting' vehicle (ZEV) and this would undermine the fundamental objective.

The hybrid-battery car has always posed these dilemmas. Meanwhile, the pure battery car continues to fall short of acceptability. The solution to the impasse could be the fuel cell. This has also been researched and tested over the years in various guises. The past obstacles have included its low power density, high cost and complexity, and slow response. However, if recent solid polymer fuel cell developments bear fruit, and if there is also success in designing small and economical methanol reformers to act as a source of hydrogen, then they could provide a liquid-fuelled 18 kW APU which emits none of the pollutant gases in discernible quantities.

Such a device would not only provide indefinite range coupled with rapid refuelling, it would also greatly enhance the performance of the electric car on two counts. Firstly, the fuel cell could operate continuously, without infringing emission laws, and therefore its power output would always be available to supplement that from the battery. Secondly, it would eliminate deep battery discharging and this would enable the cell designer to optimize for power instead of cycle life. Furthermore, batteries with essentially the desired characteristics for such a system already exist in abundance in the form of the modern sealed car starter type. The reliance of EVs on promised battery breakthroughs would probably therefore be removed once a cost effective fuel-cell system becomes available.