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Battery requirements for electric vehicles

D. F. Gosden
School of Electrical Engineering, University of Sydney, Sydney, NSW 2006 (Australia)

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Abstract

As interest grows in the possibility of electric vehicles (EVs) replacing conventional internal-combustion-engined-powered vehicles in many major cities, attention is being given to the development of improved batteries. Heavy-duty, lead/acid batteries have served the needs of low-performance vehicles, such as milk floats and fork-lifts, for many years. The demands of high performance in a lightweight vehicle, however, have increased the battery loading substantially. The performance requirements of a modern, traffic-compatible EV are reviewed and corresponding requirements on the battery discussed.

Introduction

On a number of occasions, it has been said that the development of a suitable battery for electric vehicles (EVs) is the most difficult technical challenge presented to the battery industry in recent times. If the challenge can be met, there are enormous benefits available to the industry. The replacement of even 10% of the present internal-combustion-engined vehicle (ICEV) fleet by EVs (as is envisaged in California over a 15 to 20 year period) represents a very substantial market.

One of the main issues relating to EV batteries is the large proportion of the overall product they occupy by a number of measures:

(i) Batteries represent a substantial part of the overall vehicle mass. For a typical EV using existing lead/acid technology, the battery mass is roughly one-third of the total vehicle mass. This factor is unlikely to decrease much in the foreseeable future, even when some of the new battery couples, now just emerging from laboratories, begin to be manufactured.

(ii) The initial cost of batteries is likely to continue to be a very substantial part of the overall vehicle cost. Although large-scale production will undoubtedly reduce unit costs, the battery is likely to continue to be 25% or more of the overall vehicle cost.

(iii) The relatively-limited life of EV batteries is such that if replacement cost is amortized over the life of the battery, this cost is likely to continue to be much higher than any other running cost.

Another major issue is that of energy density. The EV must carry its battery with it. In present-day EVs, about one-third of the battery energy is used just to transport the battery. To be successful, EVs will need to approach the utility of present ICEVs in as many ways as possible. Therefore, it is useful to consider ICEVs as a basis for comparison. One kilogram of petrol releases 46 MJ, or 13 kWh, of heat energy when burned [1]. For a typical efficiency of 12% for conversion to mechanical energy at

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the wheels, the useful energy is 1.56 kWh. Present EV batteries, typically provide between 30 and 50 Wh kg^{-1} depending on the type and duty cycle. For a conversion efficiency from battery-to-wheel of 80%, at best, the useful energy is about 40 Wh kg^{-1}, down by a factor of 40 on petrol. The challenge is to reduce this gap as much as possible.

EV performance targets

In defining performance targets, it is useful to consider standardized driving cycles that are intended to represent typical driving patterns. A chassis dynamometer on which the vehicle is to be tested is programmed to match the road (tyre and aerodynamic resistances) encountered in normal road operation. The vehicle is then driven on the dynamometer to follow a predetermined speed/time profile. The Australian standard cycle is AS2877 [2]; it is based on the US Federal Urban Driving Schedule (FUDS). The main part of this cycle extends over 23 min with a maximum speed of 91 km h^{-1}, a maximum acceleration of 0.147 g, and a maximum acceleration × speed product of 0.136 g at 51.5 km h^{-1}. (This latter point determines the maximum-power requirements.)

Consideration is being given to the use of AS2877 for energy consumption measurements of EVs and light commercial derivatives. No EV measurements are yet known to be available using AS2877 in Australia, and in fact, it is very difficult to obtain authentic energy consumption figures for modern EVs operating under controlled conditions. Over the past 10 years, however, there have been a small but sufficient number of measurements on EVs in various countries to make some comparisons between the energy consumption of EVs and comparable ICEVs. This procedure is useful in making a comparison between the characteristics of the respective energy-storage media in EVs and ICEVs.

Given the limitations of the EV battery system, it is necessary to find a suitable compromise where adequate performance can be achieved with the limited energy density of existing and near-term batteries. In the case of an ICEV, there is a boundary below which performance such as acceleration and top speed are regarded as unsatisfactory. Above that boundary, vehicle costs increase, mainly due to the higher cost of the engine, drive train, suspension and other items that depend on power and speed. Generally, the offsets of higher performance in terms of range and energy costs are not an issue of significance. This is not the case with EVs, however, where higher performance demands are met at the expense of reducing an already low range.

The characteristics of petrol have allowed the production of a general-purpose vehicle for use both in congested, slow-moving urban traffic and for steady, high speed operation on the open road. Whilst not optimized for either, a long period of development has produced a vehicle that achieves both reasonably well. On the other hand, EVs (at least the first generation) are likely to be directed towards city/urban use only.

As a consequence of its dedication to city operation, some performance figures for an EV may be somewhat relaxed compared with those for a similar-sized ICEV. The main issues in arriving at a suitable performance specification for an EV are:

(i) *Maximum speed*. This is the highest speed attainable by the vehicle on a flat road with zero wind under dry conditions. This is an important parameter that determines the sustainable freeway speed. Present ICEVs exhibit top speeds that are generally in excess of 140 km h^{-1}, and in some cases approaching 200 km h^{-1}. Whilst such top speeds provide some reserve for high-speed, open-road operation, they are well in excess of what is required in city operation, even on freeways. With the relatively-limited freeway network existing in Australian cities, a top speed of 120 km h^{-1} would appear to be quite adequate.

(ii) *Acceleration*. This is an important parameter in determining traffic compatibility. In congested traffic, acceleration from zero to 50 or 60 km h^{-1} is a useful figure while acceleration for, say, 50 to 100 km h^{-1}, is important for ramping on to freeways.

Since traffic compatibility is an essential requirement for successful EVs, it is useful to note acceleration figures for existing ICEVs. Traffic compatibility is important both from a safety point of view for the maintenance of uniform traffic flow and from the point of view of the EV driver who does not want to feel disadvantaged.

An examination of acceleration levels of seven vehicles considered by the NSW National Roads and Motorists Association (NRMA) to be the best vehicles in their classes for 1991 is given in Table 1.

While the acceleration rates corresponding to the above figures are rarely used in normal traffic, most drivers feel more secure if there is a reserve beyond their normal requirements.

For the time being, a value of 14 s is chosen as suitable for an EV; it is close enough to the figures for the first three vehicles to be indistinguishable for practical purposes. As will be seen in later calculations, however, the demands on the battery and propulsion system in meeting this performance are severe. Accordingly, it will be relaxed somewhat.

Another important issue in establishing the credibility of EVs is their need to be able to follow the AS2877 driving cycle described above. The most difficult point for an EV is usually the maximum-power point.

(iii) *Gradeability*. This relates to speeds at which the vehicle will ascend particular grades. It is an important parameter but is often not provided. The first consideration is the grade on which the vehicle will start and continue running. This specification relates to the ability of the vehicle to climb kerbs, get out of deep potholes, and generally negotiate substantial discontinuities in the road surface. The gradeability of EVs is often considerably lower than that of otherwise comparable ICEVs that exhibit starting gradeabilities of the order of 35%. This performance is, of course, dependent on the vehicle payload. For the purpose of this consideration, a starting gradeability of 35% for a normally laden EV is adopted.

It is unlikely that the vehicle would encounter a gradient of 35% on a continuous slope. Even the steepest of access driveways are rarely more than 25%. Accordingly,

TABLE 1

ICEV acceleration times

Vehicle	Acceleration time 0 to 100 km h^{-1} (s)
Mazda 121	14.4
Toyota Tarago	13.9
Mitsubishi Magna	13.8
Subaru Liberty	13.3
Mazda 323	11.0
Mazda MX-5	10.7
Mazda 929	10.5

the speed at which a grade of 35% is ascended can be quite low. An EV test procedure, J227, published by the SAE [3] specifies the gradeability limit as being determined from the drawbar pull that can be exerted by the vehicle on a flat surface fo 20 s while moving forward at a speed of at least 1.5 km h^{-1}. This test procedure is considered suitable for Australian conditions and will be adopted for this study.

Other considerations could be the speeds at which the vehicle will ascend gradients of, say, 5% and 10%. These data are closely associated with the acceleration characteristics. Normally, they are not specified. It will be noted that calculations in the section on propulsion-system characteristics indicate that when starting gradeability, maximum speed and acceleration specifications are achieved, the speeds at which the EV will ascend normally-encountered grades is quite adequate.

In summary, satisfactory road-performance specifications of an EV for city/urban operation are shown in Table 2.

Having derived suitable performance specifications, the loading on the battery can be determined by considering the vehicle parameters that relate to energy consumption. These are the vehicle mass (for kinetic energy), tyre-rolling resistance, and aerodynamic drag factors. For the purposes of calculation, a reference EV with the parameters shown in Table 3 will be used [4].

The mass is derived form a typical ICEV with a mass of 1 ton. When constructed for electric drive, the engine, transmission, fuel tank, starting battery and exhaust system (that, typically, weigh 180 kg) are not present. In their place, are a battery pack (lead/acid, 390 kg), drive motor, control electronics and ancillaries, giving the vehicle a total mass of 1296 kg. Two 140-kg passengers bring the operating mass to 1436 kg. (It is to be noted that a typical EV using lead/acid batteries will be roughly 30% heavier than its ICEV counterpart.)

Modern tyres have a rolling-resistance coefficient of about 0.01. (That is, the force required to move the vehicle slowly on a level smooth surface is 0.01 times the vehicle weight.) Tyres with lower rolling resistance have been produced. The types used on the GM 'I impact' vehicle are reported [5] to have a rolling resistance of 0.0048. Since tyre resistance accounts for more than 60% of the energy required to drive the vehicle in urban areas, this reduction is very significant in extending the range and/or reducing

TABLE 2

EV road performance specifications

Maximum speed (km h^{-1})	120
Acceleration time 0–100 km h^{-1} (s)	14
Acceleration rate at 51.5 km h^{-1} (AS2877) (g)	0.136
Starting gradeability (%)	35

TABLE 3

Reference EV parameters

Mass (kg)	1436
Tyre-rolling resistance coefficient	0.01
Aerodynamic drag coefficient	0.35
Projected frontal area (m^2)	2.5

battery mass. Little information is available, however, on the availability and durability of such tyres.

An aerodynamic drag coefficient of 0.35 is typical of many vehicle operating today. This figure can be reduced; the inpact exhibits a drag coefficient of 0.19. Such a body is, however, less convenient in terms of useful internal space for given external dimensions and the overall benefits in city driving are doubtful.

Road load curves

From the data given above, road-load curves can be determined. Figure 1 shows the driving-wheel tractive effort and power required to propel the vehicle on various gradients at constant speed within the range of maximum speed and gradeability specified above.

Propulsion system characteristics

From the data in Fig. 1, the propulsion-system characteristics to achieve certain levels of performance can be derived. Propulsion-system driving curves are shown in Fig. 2 in terms of the tractive effort (TE) at the wheel/road interface and road speed. The characteristic is made up of segments of constant TE and constant power. Three

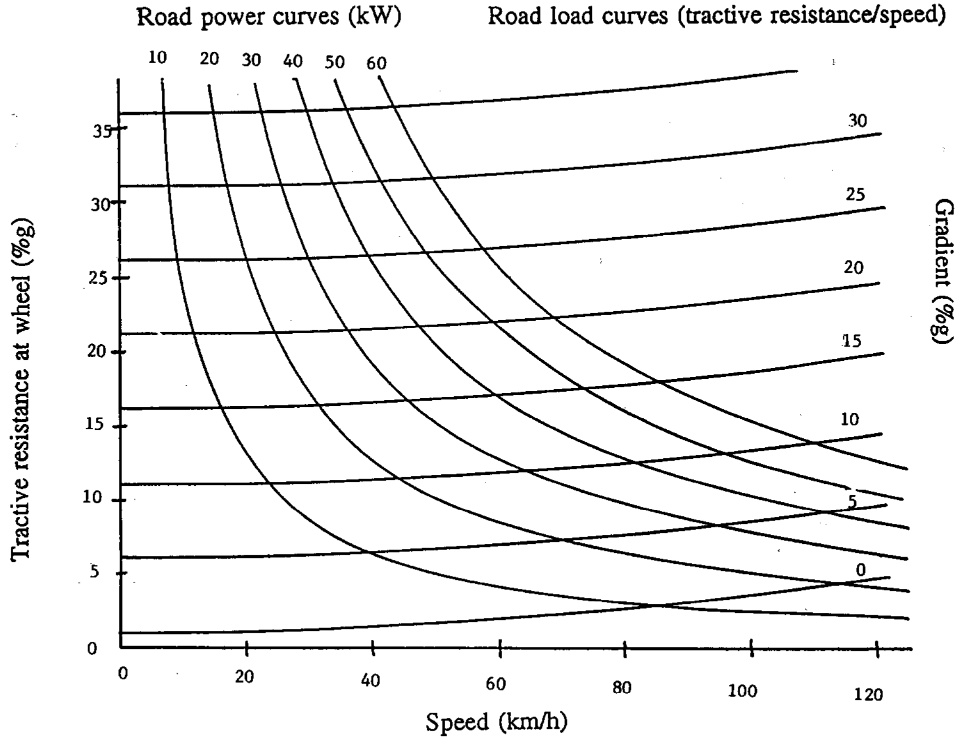

Fig. 1. Tractive resistance/power curves.

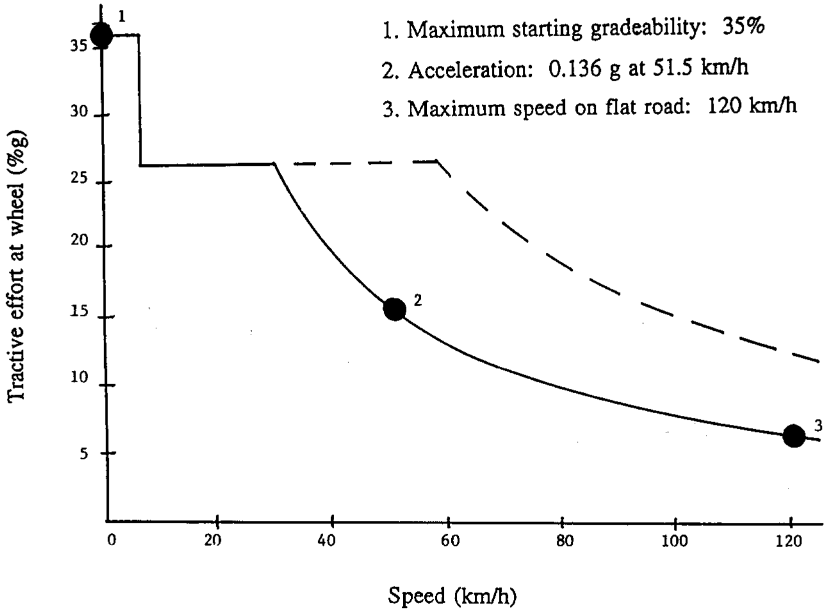

Fig. 2. Preliminary drive-system tractive effort/speed curves.

critical points of specification are shown: (i) maximum starting gradeability of 35%; (ii) acceleration of 0.136 g at 51.5 km h^{-1}, and (iii) maximum speed of 120 km h^{-1}.

Constant TE is provided at 36% g from zero to 10 km h^{-1}. This provides adequate starting and low speed gradeability. To effect some saving in the ratings of the motor and controller, the TE is reduced to 26% (sufficient to ascend a 25% grade) above 10 km h^{-1}. This level is maintained until the power reaches its maximum value, above which TE is reduced as speed increases to provide a constant-power characteristic.

Three of the four specified performance indicators are met by the solid curve on Fig. 2 which limits the output power to 30 kW. Acceleration time from 0 to 100 km h^{-1} calculated for this characteristic is 27 s, well beyond the target figure. It is necessary to increase the maximum power level to 60 kW (dotted curve) to achieve an acceleration time of 14 s. By the time the motor/controller losses are added, the power level demanded of present technology batteries of the size used in the reference vehicle (390 kg), battery efficiency has fallen markedly and frequent demands at this power level would reduce range substantially.

A maximum road power of 40 kW has been chosen as a suitable compromise. This gives an adequate margin above the AS2877 acceleration and maximum speed points. Acceleration times for 0 to 80 km h^{-1} and 0 to 100 km h^{-1} are 12 and 20 s, respectively. These are considered to be adequate for a practical EV. Figure 3 shows the relevant TE curves, together with the battery-power curves, after subtraction of an assumed motor/controller loss of 20%.

It is to be noted that these curves represent maximum-performance conditions that determine the short-term ratings of the propulsion system and battery. For a large part of the time, power demands will be less. A study is planned to determine a probability map for power demand, but this has not yet been carried out. Data is

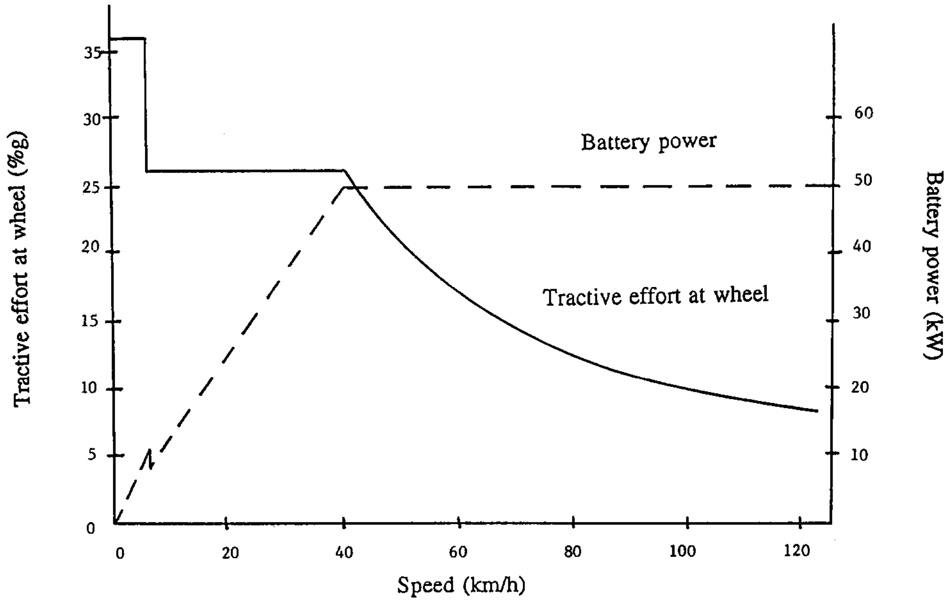

Fig. 3. Optimum drive-system tractive effort/speed curve.

available, however, to indicate that in urban driving, for 50% of time, less than 20% of maximum power is required [6].

Regenerative braking

The benefits of regenerative braking depend critically on the duty cycle on which the vehicle operates. Hard data are not readily available, but field-test reports in the region of 10 to 15% are thought to be reasonable [7].

The question as to whether a battery can successfully accept charge derived from regenerative braking depends on its characteristics, the power level and the duration of the charge. AS2877 can be used as a guide for the operation of a vehicle in an urban area. Over this cycle, decelerations of the reference EV produce up to 40 kW for several seconds. Another source of regenerative energy would be descent of a long hill. For example, descending a 10% grade at 60 km h^{-1} provides about 20 kW (after deduction of tyre and air resistance). This could occur for several minutes in some cases. A further example would be bringing the vehicle to a stop from 100 km h^{-1} over 30 s; this would provide about 15 kW.

For batteries that cannot accept the level of regenerative power available, electronic control can be incorporated to reduce it to a safe level. The vehicle, of course, still has its friction braking system, so safety is not prejudiced. The loss is in the energy that might have otherwise been recovered. Personal experience has indicated that if a battery can accept up to 15 kW (scaled for the reference vehicle and subtracting motor/controller losses) for up to 15 s, most of the possible regenerative energy available is recovered.

Battery current fluctuation

Under ideal conditions (for the battery) the current flowing through the battery would be smooth d.c. This is the only current component that conveys useful power to be external circuit. The a.c. components are detrimental. At the least, they produce losses proportional to the rms current while more damaging effects can be excess battery heating, reduced capacity and shortened life.

There are generally two a.c. components that are potentially present in the battery circuit. First, there is the variation in current due to changing road-power demands that arise from acceleration, braking and grades. Deviations from the mean current level can be up to 5 times or more for periods of up to several seconds for acceleration and braking, or several minutes for long gradients. An EV battery must be able to cope with this range. However, work is proceeding on load-levelling hybrid systems to smooth out these variations. Of most promise, if it can be realized, is the 'super-capacitor' [8].

The other source of a.c. arises from the modulation process adopted in the power-processing system to control voltage. Generally, modulation frequencies in the range 4 to 20 kHz are used. As a result, currents at these frequencies flow in the input power lines. Depending on the nature of the modulation, a.c. components in excess of the d.c. component are possible over certain parts of the control range. Unchecked, these would substantially increase battery losses and heating. Modern electrolytic capacitors with high current ratings can, however, be placed across the supply lines at the power processor input, virtually eliminating the a.c. at modulation frequency from the battery completely.

Battery requirements

In the USA, a group, the US Advanced Battery Consortium (USABC) has been formed to focus the development of improved EV batteries [9]. One of its roles has been to identify realistic goals for advanced EV batteries. Some of the more significant characteristics of batteries, and their implications in use as as follows:

- High mass/volume energy density, a measure of the operating range that can be achieved between recharges for an acceptable battery mass/volume
- High mass/volume power density, a measure of the ability of a battery of acceptable mass/volume to provide the power required for rapid acceleration and hill climbing
- Long cycle life, influences the battery cost in terms of \$ km^{-1}. At present electricity charges, it is likely that battery life costs will continue to exceed electricity costs by a factor of more than three
- Recharge time: although 'recharge while you wait' is not likely to be achieved (see re-energisation, below), it should be possible to provide a reasonable portion of recharge in 1 to 2 h and a full charge overnight
- High energy efficiency, minimizes waste and heating
- Low self-discharge rate, allows the battery to be left without attention for reasonable periods of time
- Low (zero) maintenance, in many EV demonstration programmes, inadequate battery maintenance has been found to be a major cause of failure. Ideally, the battery should be a maintenance-free 'black box'.

The goals set by USABC in these areas are given in Table 4. The mid-term objective is directed towards the 1995–1998 time frame, while the long-term objective is beyond 2000.

TABLE 4

USABC battery performance goals

Characteristic	Mid-term	Long-term
Mass energy density (Wh kg^{-1})	80	200
Volumetric energy density (Wh l^{-1})	135	300
Mass power density (W kg^{-1})	150	400
Volumetric power density (W l^{-1})	250	600
Cycle life (charge/discharge cycles)	600	1000
Recharge time (h)	<6	3–6
Energy efficiency (%)	75	80
Self-discharge (days for 15% loss)	2	30
Maintenance	zero	zero

TABLE 5

Battery performance goals of the US Department of Energy

Battery	Energy density (Wh kg^{-1})	Power density (W kg^{-1})	Cycle life to 80% capacity
Lead/acid	56	79	450
Ni/Fe	56	79	1125
Zn/Br_2	75	79	600
Li/FeS	100	106	600
Na/S	100	106	600

Energy/power density

While the USABC objectives are desirable for the production of a high-performance EV, some of the targets do exclude from further consideration virtually all the battery types that are presently being used. It is unlikely that lead/acid, Ni/Cd, Ni/Fe, Ni/Zn or even Na/S batteries will meet the energy density goals in the foreseeable future. Accordingly, the objectives tend to reinstate the notion that EVs will not succeed until a suitable battery becomes available. They discount the prospect that with some adjustment of vehicle operating patterns, even present-day batteries can suitably power a workable EV.

Is it instructive to compare the USABC goals with those set by the US Department of Energy in 1987 for batteries considered, at that time, to be the most promising, see Table 5 [10]. Recognizing the differences in the characteristics of various battery types, different goals were set in terms of what was considered realistic for the particular battery type. The energy/power density figures are specified in terms of the battery's ability to follow a current profile demanded by a vehicle following a simplified version of the US Federal Urban Driving Schedule (SFUDS) [11]. A number of these goals have already been met and are likely to be further surpassed with more development.

In most batteries, there is a trade-off between energy/power density and cycle life. Achievement of the former requires maximum electrode/electrolyte interface area and minimum inert material. Both these conditions tend to reduce the structural strength of the cell and so reduce its cycle life.

Re-energizing

Apart from the limited operating range that is available from existing batteries, the other crucial issue is the time taken to re-energize the battery.

At present, virtually all batteries being used in EVs are re-energized by electrically recharging them. While there have been a number of claims that Ni/Cd batteries are able to accept a full charge in as low as 15 min, generally, several hours are required. There are two major difficulties associated with fast charging. The first concerns the battery's ability to accept a high-charging current, particularly as full charge is approached. A rough, but widely accepted, rule-of-thumb for a lead/acid battery is that provided temperature rise is adequately controlled, the battery can accept a charging current numerically equal to the ampere-hour capacity removed. For example, the initial charging current for a battery from which 100 Ah has been removed can be as high as 100 A. As charge is restored, current must be reduced. The current profile followed is exponential with a time constant of 1 h. On this basis, 85% of the charge removed can be restored in 2 h. Na/S batteries do not exhibit the same end of charge problems associated with lead/acid but still have a charging-current limitation that requires 2 h for full charge. Maximum charging rates for other developing batteries have not yet been fully determined. It is unlikely, however, that electrical recharge times can be much faster.

The other problem associated with fast charging is that of providing an adequate electricity supply. Simple calculations on refuelling an ICEV reveal that at a fuel-flow rate of 40 $\mathrm{l\ min^{-1}}$, the equivalent power flow in the fuel stream is over 30 MW. Even when only some 12% is converted to useful work, the effective fuel-flow power is 3.6 MW. To provide anything approaching this power level with electricity, particularly when re-energizing several vehicles at the same time, would be quite difficult.

As has been pointed out on many occasions, vehicles generally spend far more time parked than they do moving. In urban areas, electricity outlets are already very widely available and in many cases, even now, it is possible to connect an EV to a power outlet in many places where it might be parked. The idea of 'biberonnage' or opportunity charging has been studied for many years [12]. In linking parking and battery charging, GM Chairman, Robert Stempel, has said 'We need to stop thinking gas stations and start thinking about refuelling as part of the parking operation. You'll either be driving or you'll be plugged in, whether you're at home, at work, at the mall or in a restaurant. Frequent opportunities to recharge will lessen consumer concerns about range' [13]. From personal experience with the Sydney University ETV, it has been found that with a little planning of a journey, it has generally been possible to find a power outlet at many places the vehicle is likely to visit (e.g., home, work, business and social visits). With the type of infrastructure policies such as those being introduced in Los Angeles, it should be possible to connect an EV to the mains supply at many points, and so extend the useful daily operating range well beyond the single charge range.

Several battery types lend themselves to means of re-energization other than by electrical recharging. Techniques may encompass complete battery exchange, or electrode/electrolyte replacement. Whilst such techniques may be suitable for single-operator fleets, where exchange facilities can be provided at a base, they would not be available for free-range vehicles without a considerable investment in distributed exchange facilities.

Conclusions

The benefits EVs can bring in improving the air quality in our cities and diversifying transportation energy sources are generally accepted. There is still a wide gap, however, between what is expected in terms of EV utility and cost and what can be achieved with developing battery technology. The challenge for all parties working in the field is to contribute to the narrowing of this gap.

Acknowledgements

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