Research Article

An Electric Vehicle as a Commuter Car

E.A. Mallia and D. Schembri
Department of Physics, University of Malta, Msida MSD 06, Malta.

Summary: *A small internal combustion engined car converted to work off batteries was test driven over a four year period. Intensity of use was about half that of conventional cars, the main vocation of the vehicle being a commuting one. Despite the lack of regenerative energy recovery, the EV proved capable of journeys of 50-60 km length on full charge, even when numerous gradients were involved. Energy consumption under a wide range of traffic conditions was about 0.1 that of an ICE car considering only on-board energy. For the total fuel cycle the EV consumed 0.4 of the ICE car; this figure would drop to 0.3 with regenerative energy recovery and to 0.26 with the best available generating efficiency. For purely mains charging, EV CO2 emissions are 50% of an ICE car. However it was shown that significant amounts of charge could be obtained from small PV installations, in which case average CO_2 emissions could be as low as 15% of those from an ICE car.*

Legal problems with EV registration were finally solved in an ad hoc fashion. Revision of registration criteria for electric vehicles is urgently required.

Keywords: electric vehicle, energy consumption.

Introduction

The internal combustion engine is at serious disadvantage in present road traffic conditions. As car numbers on roads and urban sprawl have increased, average journey speeds have gone down. At low speeds, fuel consumption will be far from optimum, with large increases in the emission of certain pollutants. Where catalytic converters are in use, short journeys may prevent them from reaching their working temperature, allowing pollutants to filter through at low conversion rates. Cooling systems may overheat in slow traffic, particularly in summer, with indiscriminate use of car air conditioners. In such situations a battery-powered car can offer significant advantages.

Local conditions

Local conditions correspond essentially to european urban driving at best, and in town and village cores, with speed limits of 25kph, to inner city or city centre conditions on a much reduced physical scale. In March 2001, the number of licensed motor vehicles exceeded 248,000. There were 43,200 commercial vehicles and 183,400 private cars, among which were some 7000 cars with engine capacities above 2 litres (NSO, 2001). These latter are rather unsuited to local roads, where there are few stretches that are at all safe at speeds above 120kph. With 260km of arterial road we have some 1.4m of road per car, without allowing for other types of road vehicle. Congestion may therefore be acute on main roads at rush hours, particularly where roadside parking is allowed.

For an assessment of the usefulness of an electric vehicle (EV) as a commuter vehicle it is worthwhile to look at mode and intensity in local use of cars. There is as yet no very comprehensive source of such information. What follows draws on 1996 observations of the Traffic Section of the Planning Authority (PA); on results of the 1998 household travel survey conducted by the PA; on answers (52) to a questionnaire circulated by students from James Madison University (Abbott et al., 1999); on answers (75) to a questionnaire circulated among university staff (Mallia, 2000).

While the PA 1998 survey is by far the most statistically significant, the other sources contain some information which is particularly relevant to our purposes, even if the weight that can be given to them is limited because of the small sample size.

The JMU and university staff surveys suggested that mean distance covered in a year was close to 10,000km, with 75% of respondents covering between 15km and 40km every day in some 3-4 journeys per day. There was some ambiguity in the responses relating to this last parameter simply because respondents did not always make clear if "journey" meant single or return.

Average speed information was and still is rather sparse. Short time sequences (PA, 1996) for a main road through Mosta gave 27kph, comparable to the 30kph mean speed in European cities (MEET, 1997). On the other hand, along Aldo Moro Road, linking Marsa with Paola and Luqa, average speeds were close to 50kph, even if there were cross-roads (now controlled by traffic lights) at one end and a roundabout at the other end just 1km away.

The Electric Vehicle (EV).

In original form the test vehicle was a small, four seat petrol-engine car (704cc) of 1989 vintage with rear wheel drive. The petrol engine, mounted at the rear of the car, was replaced by a 6kW (8 HP) DC series motor run at 60V. Despite some loss in efficiency, the original gear box with stick shift was retained for two reasons. The 6kW motor with only the gear ratio in the differential would be unable to carry the vehicle up the steepest local gradients with two passengers and a 240kg battery load. That would have imposed significant limitations on the car's area of use. In practice the car ran in second and third gear; first was only used for steep gradients and top not at all because of insufficient motor torque. In this respect the electric motor, with high torque at low RPM, behaves differently from the internal combustion engine (ICE). Top speed on the flat was 65kph.

Retention of the gear box also greatly simplified coupling of motor to drive, requiring just a faceplate and motor-gear box shaft connection, with the motor itself fixed to the engine mounting bracket (see Figure 1). The original flywheel was retained with rebalancing, after some 20% of its mass was removed by cutting out annular sectors. No ehanges were made to the rear suspension (coil springs); the front suspension was strengthened with an extra leaf after the successive destruction of two front traction batteries by heavy vibration from poor road surfaces. Out of a total of Lm120 spent on maintenance over the four-year running period, most went into strengthening suspension and brakes. Consumption of gear box oil amounted to 4*l*.

A total of five 12V 110Ah gas-recombination Pb-acid batteries with a nominal 6.6kWh and a realizable 5.2kWh to 80% depth of discharge (DOD), provided the traction energy. One battery was accommodated at the front and four in place of the rear seats. Placed in the car boot, these batteries would have been outside the line of the rear axle; 192kg in that position would have made the steering dangerously light and put excessive weight on the rear wheels. For almost all of the test period, one of the rear traction batteries doubled as services battery. Two 15Wp PV panels connected in parallel and bolted on the car roof rack supplied small amounts of extra charge to the services battery. For the final ten months of the test period this arrangement was substituted by a DC/DC converter delivering 13.2V with a 48-65V input from the battery pack.

The motor controller did not cater for regenerative current, and there was no on-board charger. This required some care in undertaking specific trips, a concern that would not be present in a properly designed commuter vehicle. Battery charging could draw on three different sources: a standard voltage-regulated charger (600W) working off the mains; photo-voltaic (PV) installations of 250Wp and 330Wp; static battery packs charged by the PV panels when the vehicle was on the road.

Electric Vehicle Use

Over a calendar period of 4 years which included 44 motoring months, the EV covered a total of 16,378km, which suggests an intensity of use lower than normal for a private car. The strongly-commuter nature of the use

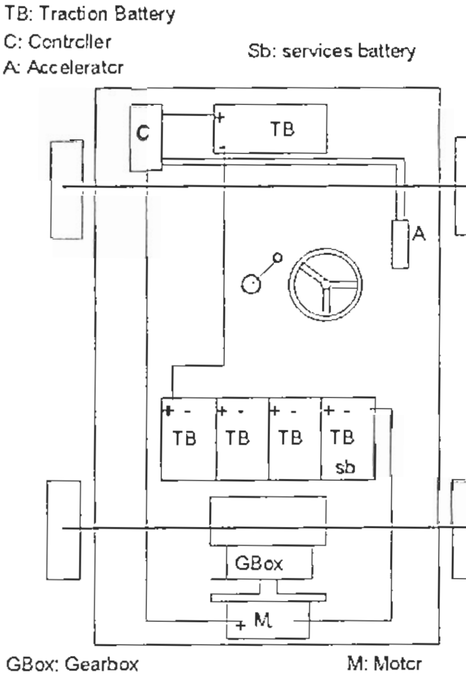

Figure 1

can be seen from Figures 2 and 3: the one-way journey to the university campus was 5.9km long.

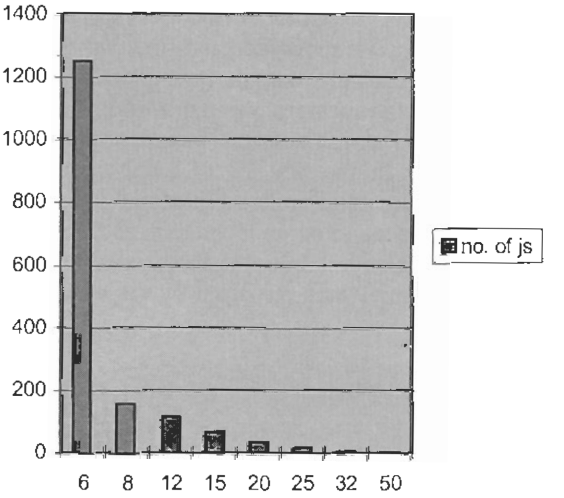

Figure 2

Over balf (53%) of the total distance covered during the test period was generated in journeys of 6km or under. The next three journey lengths– 8km, 12km and 15km – combined provided a quarter (25.6%) of the distance covered. These proportions reflect the central position of Campus and Attard in relation to the south and soutb east of Malta, where most social facilities in everyday use are situated.

There was at best only a very minor influence on the journey pattern from the limited range of the EV. The journey pattern for the 1738km covered with solar charging, when one would expect the general level of

battery charge to be lower than with mains charging, is very similar to the general pattern (Figure 4); so is the daily travel distance: 12km/day for the whole of the test period and 13km/day for the "solar" period.
The test period stretched from November 1997 to November 2001. Over this interval the major use of the vehicle was for normal commuting needs. Over September- October 1998 and April-May 1999 an extensive series of commuter journeys were monitored in detail. These provided determinations of energy consumption and range of the EV under local driving conditions. In addition there were two journeys of 50km (Campus – Cirkewwa return) spaced by two years to test battery ageing, as well as a set of some 50 test trips in the period December 1999 to March 2000. These latter also involved direct comparisons with a petrol-engine version of the EV.

The monitoring system underwent some development during the test period. In the first version, battery and motor voltages, motor current and motor and controller temperatures were sampled every second and average values for 10-second periods were stored. Combined with car odometer readings, these data were used to work out energy consumption and average speeds over sections of journeys and over whole journeys. For the 1999 – 2000 test runs, instantaneous speed was added to the recorded data – while retaining the analogue indication of the normal car speedometer. The speed data could be combined with the sampling time to provide another measure of total or partial distance covered. Data were recorded and stored at 1s intervals after it was found that during periods of strong acceleration 10s averages were distorting the current-time curve. As a result, instantaneous power and total energy values in the first set of monitored journeys contained systematic underestimates of up to 8-10%, actual values depending on magnitude and frequency of acceleration episodes. Initially, the maximum length of monitored journey was restricted by the 40-minute life of the computer battery. With use of two batteries, up to 90 minutes of recording was possible, allowing monitored return journeys to the northern and southern ends of the main island from the university campus (sample trace shown in Figure 5).

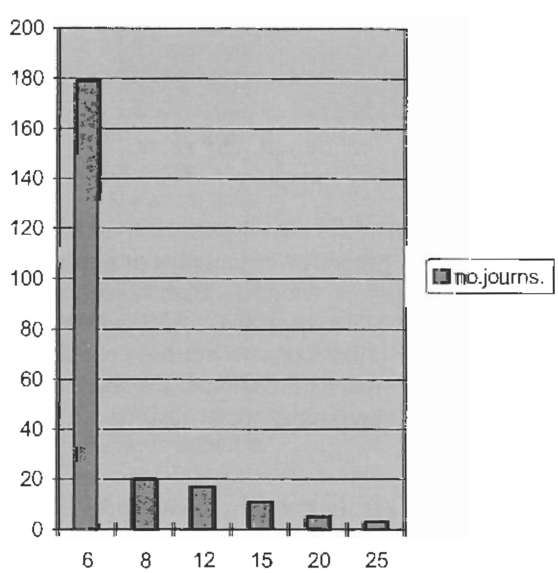

Figure 4

Capacity tests on the surviving four rear-mounted batteries were run during February 2000, after 27 months and 9200 km of running. It was not possible to compare the bench results with those expected from cycle life specifications provided by the makers. The batteries were seldom fully discharged; while opportunities for solar charging were hardly ever missed. That style of use, imposed to a large extent by the commuting vocation of the vehicle, does not allow a credible estimate of number of cycles the batteries have been put through.

Nichrome wire (SWG 8) was used as load, with a length chosen to obtain a current of about C/5 (22A) from a fully charged battery. Measurement of current and terminal p.d. was continued until the latter reached 10.2V, which corresponded to 80% DOD according to specifications. The capacity under these conditions was found to lie between 100Ah and 105Ah; the batteries had lost up to 10% of nominal capacity. Some warping of the outer casing, which must reflect internal plate buckling, was also evident.
Motor maintenance was restricted to occasional removal of graphite dust from brush erosion. At the end of May 2001, the brushes had eroded by about 2mm in 32mm. The original set were left in place. During the four year test period, there were no motor or controller failures.

Energy Consumption
The nominal energy content of the 240kg battery pack was 6.6kWh, of which 5.3kWh were available by 80% DOD. This energy content is equal to that of 0.57*l*. gasoline (Goodger, 1982). After a period of two months running, the batteries were drained and then slow-charged over a period of 22 hr. The mains wattmeter registered 7.9kWh, which indicated a transfer of 5.1kWh into the batteries (see below). The vehicle was then driven for a period of 6 days without further charging. The trips included a 21km run (Campus-Marsaxlokk-Campus);two journeys Attard-Mosta-Campus; two Attard-Campus return. After the final return to Campus, individual battery voltage was close to 11.0V. This represented a residual range of about 5km, which could only be covered at low speed. The total distance actually covered was 73km, giving a specific energy consumption of 0.07 kWh/km.

For practical purposes the range with full charge was taken to be 65km. This served not only to lessen the risk of getting caught on the road with exhausted batteries, but also to have a minimal hill climbing ability in reserve, as one of the approaches to Campus involved a climb out of Msida Valley. In fact the longest journey undertaken was Campus-Cirkewwa return (56km); the

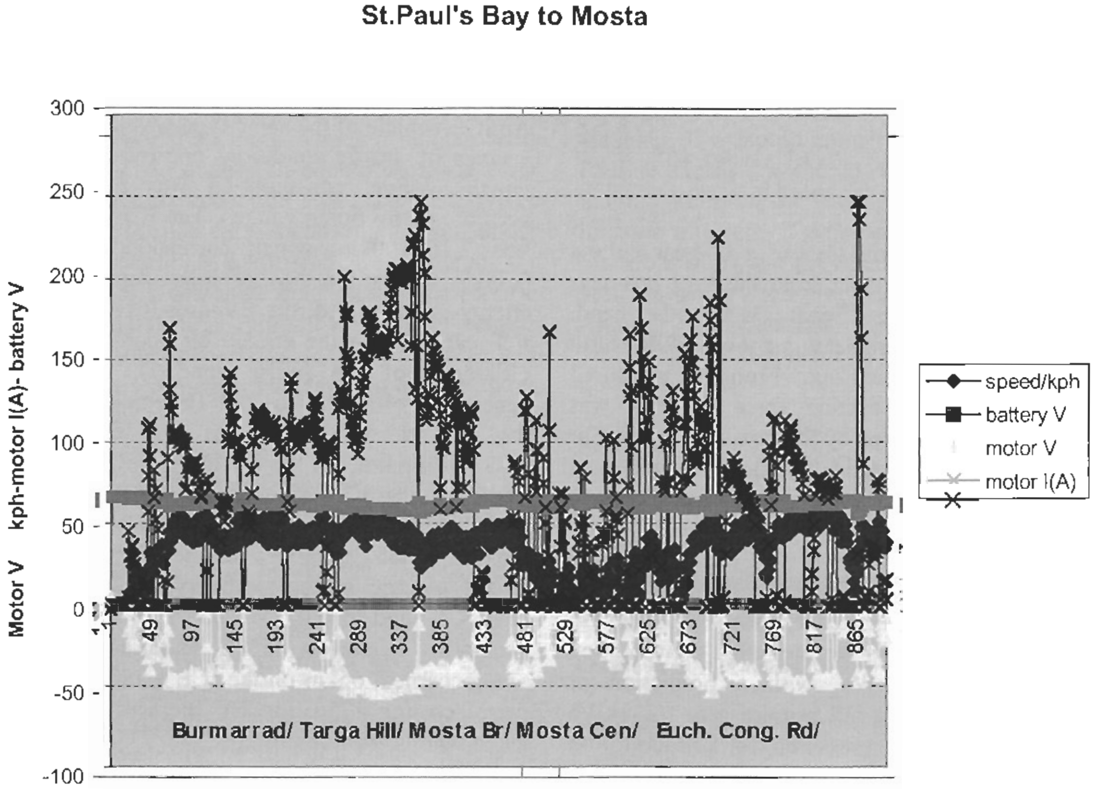

Figure 5

second longest was a circular run from Campus to Hal Far to Gudja (Airport), to Attard and back to Campus (43km), with significantly fewer hills than the first.

In general the specific energy consumption (SEC) is dependent on style of driving, on average speed, on gradients and on car occupancy. On strictly commuter trips, usually during morning and evening rush hours, average speeds were low for two reasons. Part of the route ran through narrow village streets with a 25kph limit; while the numerous roundabouts on the Birkirkara by-pass obstructed free flow. Average speeds were below 30kph, compared to 40kph for Sunday trips over the same stretch. However, superposed on average speed are the effects of the detailed driving cycle. For instance, in steady slow (28kph) and fast (43kph) runs on the Birkirkara by-pass at times of low traffic, SEC ranged from 0.027kWh/p.km to 0.045kWh/p.km. The latter, though representing a high-speed run, is at the lower end of SEC for commuter trips, where average speeds were below 25kph but acceleration episodes were much more frequent. This situation would have been modified if regenerative braking were available, but it is unlikely to have been reversed. Urban driving cycle ranges for current EVs are invariably shorter than country cycle ones. On the other hand, the use of super capacitors as a buffer between batteries and motor, with increased energy recovery from regenerative braking and the batteries spared the current peaks required for acceleration (Mestre and Astier, 1998), could have a major effect in improving SEC in urban driving.

The longer runs with full occupancy show off the EV at its best in terms of SEC. Over journeys of more than 15km without long gradients, average SEC was 0.032kWh/p.km, which is close to the SEC of a manual bicycle (Lincoln, 1973), but over twice that of an electric bicycle (Wegmann, 1998). For the longest runs: Campus-Cirkewwa return, with just driver on board, SEC ranged from 0.065kWh/p.km to 0.083kWh/p.km. The increase from the average quoted above was caused by the number of hill climbs along the route. By way of comparison, the SEC for electric cars (Peugeot 106, Citroen Saxo) in long term use in the hilly district of Mendrisio, southern Switzerland, was 0.24kWh/km (Wegmann, 1998). Taking these EVs as typical in terms of annual distance covered (12,000km) and energy consumed (2400kWh), 7500 EV would account for 1% annual electricity production (Enemalta, 2000), which is well within the recent 4.5% annual increase in consumption (Fsadni and Mallia, 1999). Overnight (2300-0700hr) charging of half this number of EVs would provide Enemalta with significant load levelling.

Predictions of energy consumption on gradients or on the flat could be made after determinations of the vehicle drag (C_d) and rolling friction (C_r) coefficients. For determination of C_r, the vehicle, with a 2.3bar tyre pressure, was pulled at a steady speed on the flat while recording the traction force on a spring balance; air drag is insignificant at such low speed.

The second method involved timed decelerations over the speed ranges 50kph to 40kph and 40kph to 30kph. Both coefficients were calculated from timed decelerations, with a first assumption that $C_d >> C_r$.

The values finally adopted were $C_d = 1.25$ and $C_r = 0.01$. For running on the flat the power required could then be estimated as

$$P(kWh/s) = 9x10^{-6}v^2 - 2x10^{-5}v + 9 \times 10^{-5}$$
with v being the car speed in $m.s^{-1}$.

From deceleration times with the car in 3rd gear and out of gear, the retardation arising from the gear box was deemed to be negligible in 3rd gear. On the other hand, for use on long or steep gradients, unpowered downhill runs in 1st gear were carried out. From the measured average acceleration, a friction force of 95N was calculated as being produced by the box in 1st gear. For use on gradients the weight of the car with two passengers and the height rise were combined to determine the energy expended.

The usefulness of the above energy estimates can be seen from a number of examples. For the short steep hill between Attard and Zebbug the measured consumption in first gear was 0.20kWh, with a prediction of 0.19kWh; for Santa Lucija hill in third gear 0.31kWh predicted against 0.29kWh measured; for Selmun hill in first gear, a measured value of 0.37kWh against a prediction of 0.34kWh; for the climb from sea level at Ghadira to Mellieha by-pass in second gear a measured energy consumption of 0.41kWh against a calculated value of 0.40kWh for third gear.

The two Campus-Cirkewwa return journeys spaced by two years clearly demonstrate battery ageing. In April 1998, the return leg ended at Attard (48.5km), with the battery voltage at 59.8V, and was then continued to Campus the following morning without recharging, battery voltage being at 59.0V on arrival. In the April 2000 run, battery voltage had dropped to 55V at Bugibba (39.5km), with values as low as 35V while running uphill into old St.Paul's. In fact the run was terminated at Bugibba and the batteries recharged overnight before continuing to Campus.

For a complete estimate of energy consumption, a measure of the charging efficiency has to be obtained. The energy input into the charger was read off a standard mains wattmeter, while energy transferred to the batteries was measured by an integrating power meter. A series of 47 monitored mains charges gave a value of 0.67±0.06 rms for the mains charging efficiency. Towards the close of the test period a pulse charger was installed, working at a frequency of 6Hz with peak current pulses of 14A. Apart from a doubling of the charge transfer rate, the charging efficiency increased to 0.8.

The intensity of use of the EV did not require daily charging. However, with charging facilities at home and on the university campus, any time the EV was parked at either station it was put on charge: mains, direct solar or indirect solar through storage batteries. With a developed infra-structure for Evs, work places could have charging points; house charging points could be an ordinary mains power socket in a garage.

An ICE vehicle of the same type was used for a week in a range of traffic conditions and over various journey lengths. Fuel consumption was measured on the accurate petrol pump gauges. The ICE car consumption was 7.16*l*/100km, which corresponds to a SEC of 0.33kWh/p.km for two persons. As far as on-board energy is concerned, the EV uses 0.1-0.2 of that of the ICE car. Getting the energy on board with a charging efficiency of 0.8 (pulse charger), together with a generation efficiency of 0.3 (Enemalta, 2000), leaves the EV at 0.133kWh/p.km and the ICE car at 0.337kWh/p.km, i.e. the EV has a SEC of less than half (0.40) of the ICE car. The EV SEC would drop to 0.102kWh/p.km with the installation of regenerative braking which capitalizes on one of the major strengths of the electric motor (recovery of 30% of available energy), and to 0.07kWh/p.km for the best available generating efficiency (45%). As far as actual fuel costs are concerned, 65km on the ICE vehicle require 4.5*l* of petrol costing 175c; the EV requires 8kWh which, if taken wholly from mains cost 36c.

From the point of view of CO_2 emissions, the transferred emissions from the EV depend on the source of electricity or more precisely on the source mix. Clearly a solar or wind source is essentially emission-free. In our national mix, an average fuel consumption of 0.3kg/kWh generated would carry a penalty of 120g/p.km of CO_2 for the EV. The ICE counterpart would produce about 230g CO_2/p.km. This CO_2 cut-back factor (0.52) for the EV can be compared with a value of 0.35 for European city driving and generation mix (Lestienne and Vergels, 1998) and with 0.5 for the US situation (Mackenzie, 1994).

In our case mains charging was supplemented by PV charging to a varying extent, depending on weather and on travel requirements. Over the period May to November 2000, for instance, the EV covered 1700km. with PV charging only. Transferred emissions were essentially zero. On the other hand, from January to June 2001, 2046km were covered on a mix of mains and solar charging. With a mains contribution of 94kWh, CO_2 emissions were down to around 40g/km, less than a third of the value for mains-only charging. As for other important pollutants from car emissions, the mitigation of these by EV use has been discussed elsewhere (Mallia,1999).

Legal aspects

Throughout most of the test period, the EV was registered under its original ICE guise. The car register required engine power and capacity; the motor has no analogue of the latter parameter. The 'solution' finally adopted was to translate motor power into 'engine capacity' via the equivalence 0.75kW = 100cc and using 'electric' as the fuel. Sometime after the registration of the car as an EV, the registration tax for new (battery) cars was reduced from the 65% for ICE models to 16.5%. Hybrids, of which there is at least one on the road, do not qualify for this reduction. On the other hand, electric motor scooters, of which a number have been sold locally, do qualify. It should be made clear however, that this tax reduction still leaves EV prices well above those for ICE cars. A car selling at just under Lm4000 in a petrol ICE version was offered for Lm10,000. Vehicles designed from scratch for electric drive still cost 20%-50% more than an ICE vehicle offering comparable space. This cost disadvantage can be mitigated by fiscal measures related to import duties and registration tax.

Engine capacity should be removed from the car registration form, leaving just engine/motor power in kW. However, if that parameter is retained, the equivalence formula should be revised. As it stands, there is a strong discrimination against EVs, both converted and intrinsic. For instance, conversion of a 1100cc ICE to a 15kW electric motor gives a 2000cc equivalence. This changes the road tax bracket of the car in an upward direction. The same handicap would operate against an electric version of a 1000cc ICE with a 15kW motor. Such discrimination goes against any policy of favouring EVs for their environmentally friendly qualities. In France for instance, where there is the largest EV fleet in Europe, EVs are registered as motorcycles, irrespective of motor power.

Conclusion

Under local traffic conditions a small EV provides a number of advantages for use as a commuter vehicle. With short distances, low average speeds and a number of short journeys every day, the EV has been shown to offer a flexible alternative to present ICE cars. As it combines low running and maintenance costs with reduced and transferred emissions of most traffic-related pollutants and low specific energy consumption, the EV is particularly suited to congested urban driving conditions. Transferred emissions can be reduced further through utilization of renewable energy sources. On the other hand, capital costs are still daunting for most available models. Low volume production is a principal cause; while other than lead-acid – with low cycle life, and low power and energy density—most battery types are still expensive. Another aspect of capital cost, which has not been treated here, lies in the choice between DC and AC drive systems. While the latter offer the highest efficiencies, they introduce high cost elements like inverters. At the present stage of the market, capital cost rather than relatively small gains in efficiency and range, may control the growth of numbers.

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