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Chapter 10

REAL-LIFE COMPARISON BETWEEN DIESEL AND ELECTRIC CAR ENERGY CONSUMPTION

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ABSTRACT

Vehicle electrification is one of the strategies with higher potential for increasing the efficiency of vehicle powertrains, reducing the dependency on dwindling fossil fuel sources and meeting stringent emissions targets set by policy makers. Despite all the theoretical assessments and manufacturer's claimed efficiency and emissions records of current vehicles, there is a lack of data concerning real life comparisons of Electric Vehicles (EV) against Internal Combustion Engine (ICE) cars.

A test program comparing the energy consumption of an EV and a diesel powered (ICE) car was carried out.

Both short (at levelled ground and 6% up-hill) and long distance tests were performed for several fixed vehicle speeds. Measurements enabling the assessment of average energy consumption, required power and energy suplied were performed for both vehicles.

Results indicate that in terms of vehicle use (Tank-to-Wheel perspective) the electric powertrain is significantly more energy efficient than the Diesel powertrain, although the difference between the two is less pronounced for higher power events.

Keywords: Electric Vehicle, Energy Efficiency, Energy Consumption.

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INTRODUCTION

Energy and Environmental Concerns and Policies

The expansion of car traffic in the last decades has been arising serious environmental concerns over the increase of greenhouse gas (GHG) emissions, urban air pollution and dependence on dwindling fossil fuel reserves. The oil crises of the seventies, along with the concerns over the volatility of oil prices and the security of fuel supply from politically unstable countries has further spurred the quest for increased energy efficiency and low emission alternatives to conventional fossil fuel-based powertrains [1][2].

Several national and international agreements and policies have been put forth in order to place even more stringent limits on fuel consumption and/or CO2 emissions of vehicles. Such was the pioneering Kyoto Protocol at the global level or the Corporate Average Fuel Economy (CAFE) regulations in the US [3]. In the European Union voluntary emissions agreements celebrated between the European Commission and institutions like the European Automobile Manufacturers Association (ACEA) were later followed by mandatory regulations on emission performance standards for new passenger cars [4].

Increasing the Energy Efficiency of Conventional Powertrains

A first approach for decreasing vehicle emissions is by increasing the efficiency of the Internal Combustion Engine (ICE). Engine downsizing and turbo-charging are strategies that have proved to be effective in this respect [5]. Also the strategy of overexpansion studied by the group, especially if combined with variable compression ratio and variable valve timing, has a good efficiency potential, as efficiencies higher than those typical of ICEs may be obtained with a gasoline engine over a broad portion of the engine map [6][7]. There are also the strategies which increase the efficiency of the powertrain by harvesting some of the thermal energy normally wasted through the tailpipe of vehicles and converting it into electricity to reduce alternator use. This can be done namely with Organic Rankine Cycle (ORC) turbines or Seebeck effect thermoelectric generators. The authors has been working in some of these promising technologies [8][9] but they still need to be further developed before they become mature for vehicle use.

Despite the promising advances in fuel economy technologies it is expected that the automotive market will grow steadily in the next decades, mainly because of increasing standards of living in rapidly developing economies, such as South Eastern Asia and South America. So, between 2000 and 2050 it is expected that the population will grow 1.7 times, but the number of cars is expected to increase even more (3.6 times) [10]. So, it seems that the sole increase of conventional powertrain efficiency will not be sufficient by itself to meet the current medium to long term emission and efficiency goals. Alternatives not relying exclusively on the combustion of fossil fuels need to be considered.

Improving Efficiency through Vehicle Electrification

An increasingly higher degree of vehicle electrification (also called vehicle hybridization) is one of the options which seems logical to take in order to meet the aforementioned targets and diversify energy sources. Electrified vehicles are more efficient than ICE ones namely under urban traffic since they have no idling losses, no unefficient clutching at starts (they have good low end torque) and they can recover a portion of the braking energy through regenerative braking [1]. In fact, hybridization has been quite an effective way of some sports vehicle brands to meet emission standards without sacrificing the performance figures of their vehicles. For instance, the soon-to–be-sold flagship model of Porsche, the 918 Spyder, will be a plug-in hybrid capable of a combined power of 652 kW (887 hp), attaining 0-100 km/h in under 2.8 s. However, its New European Driving Cycle (NEDC) consumption has been rated at only 3.3 L/100 km with CO2 emissions of just 79 g/km [11].

Well-to-Wheel Approaches

Of course, the aforementioned emission and consumption figures require further analysis, since they only reflect the gasoline's consumption and emissions during vehicle usage. The electric energy charged from the power grid into the vehicle's batteries will also have associated emissions at the production, transportation and distribution stage. Even if only the emissions during vehicle usage are the basis for automotive industry mandatory goal compliance, a Well-to-Wheel (WTW) energy efficiency and emissions computation should be used if the full record of primary energy consumption and CO2 emissions of vehicle Life Cycle must to be quantified [12]. The WTW analysis may be divided into Well-to-Tank (WTT) and Tank-to-Wheel (TTW) phases.

Well-to-Tank Phase

The energy spent to extract, refine and supply gasoline and diesel fuels in Europe is around 0.08 and 0.10 MJ/MJ, respectively, which yields WTT energy efficiencies of 93 and 91%, respectively [13].

In EVs the WTT acronym is used analogically of course, meaning the path from the primary energy source down to the vehicle's energy storage system. While the energy conversion efficiency of hydroelectric dams can surpass 90%, the efficiency of the most advanced combined cycle plant (gas + steam turbine) in the world hardly surpasses 60% (typical efficiencies for new facilities is 55%), while modern coal fired steam turbine plants fall within an average 44% efficiency [13]. There is also the efficiency of electric energy transportation, around 92% [14].

Regions with clean electricity production, namely from renewable sources (as in the case of Portugal), will potentiate the global emissions cut obtained with vehicle electrification [15]. Of course, these values would not be as intense in regions which display poor electrical production efficiency or which heavily rely on carbon-intense power sources [13].

In the case of Portugal's electricity production in 2012 (provider EDP Universal, market leader) the emissions linked with electricity production averaged 229 g/kWh (40% from wind energy). During that year the monthly average roughly varied between 100 and 300 g/kWh, with the lowest record having been obtained for peak wind energy production and vice versa [16]. In comparison, the EU-mix calculations made with 1999 data (before heavy investment in low carbon technologies gained momentum) held overall energy conversion efficiencies around 35% and emissions of 430 g/kWh of electricity produced [13]. The EU study found that only emissions in excess of 850 – 900 g/kWh would cause the EV to be worse than an ICE car. Also, WTW GHG emission savings of up to 58% would be possible to obtain with an EV instead of an ICE car for the EU-mix emission conditions [13].

Tank-to-Wheel Phase

Despite the importance of the complete WTW analysis for a global evaluation of the merits and drawbacks of vehicle electrification, the scope of the present work has been reduced to the TTW measurements of the energy consumption related to vehicle use, that is, the energy which has to be supplied to the vehicle by the fuel pump / electric charging station in order to complete a given driving schedule, or the average power needed to cruise at specified driving conditions of speed and road slope. Other studies have focused on the global WTW analysis of plug-in vehicles [12][13][15][17][18].

The efficiency comparison between an ICE car and an EV is not straightforward. In each vehicle type a chain of processes of energy supply and conversion take place until the energy supplied to the vehicle is effectively used to move the vehicle. Each one of these processes has a given energy efficiency which is not always easy to quantify as it depends on various factors, some of which are very difficult to quantify.

Supply and Charging Efficiency

ICE cars have nearly 100% energy supply efficiency since almost no fuel is lost during refueling (especially in the case of diesel which is non-volatile), nor does the fuel lose any energy content in the process. The same is not true for EV, since there are energy losses in the process of recharging the batteries, mainly due to the charger and to the internal resistance of the battery cells, around 89% and 94%, respectively [14]. But surely these values will vary significantly according to the charging mode (slow / fast) and the battery chemistry [14].

Energy Conversion at the Battery

In an EV the energy conversion efficiency of batteries under discharge depends on factors such as the battery State-of-Charge (SOC), the discharge rate, the battery State-of-Health (SOH) or the battery temperature. This temperature is affected by the ambient temperature and also increases during both the charging and discharging processes, even within nominal conditions of voltage and current [19]. However, the problem of the battery temperature increase is more critical during the batteries discharging process, mainly because greater discharge rates might occur and considering that this process is strongly dependent of the driver behavior [20].

The high temperatures on lithium batteries cause degradation during their lifetime, and the cold temperatures reduce their power and energy output, limiting the performance and the EV driving range autonomy [19]. In order to ensure that the batteries can operate in a broad range of discharging rates and external temperatures, it is essential to use thermal management systems for the batteries, to increase the batteries efficiency, safety and lifetime [19].

Electric Motor and Controller

Regarding the EV powertrain, due to the technological advances in power electronics and electric motors powertrain efficiency figures are now generally above 89%. This comprises the combined efficiencies of the power controller and the motor [14]. Like with the ICE car, the efficiency of the electric motors will be mainly affected by the position in the torque and speed map. High speeds will result in high mechanical losses, while high torques will require high currents, enhancing the losses due to Joule effect [22].

ICE Engine

ICE cars typically display much lower energy efficiency than electric motors when converting the incoming energy (chemical energy contained in the fuel / battery) into traction mechanical energy through the motor / engine. The efficiency of thermal engines is limited to a theoretical maximum (the Carnot efficiency, around 60%) which is much lower than typical electric motor efficiency (which has no theoretical limit). The engine efficiency is very dependent on the region of the engine map is used during driving. Typically, efficiency will top near full load conditions (accelerator pedal fully pressed) and moderate to medium engine speeds. For these conditions a gasoline engine will display efficiencies around 33%, while diesel engines often surpass 40% [21]. However, average efficiencies will fall significantly, especially under urban driving or high performance driving. Some sources cite an average efficiency ranging from 12 to 20% [18]. Specific emissions of Diesel fuel are around 264 gCO_2/kWh, with the volumetric energy content of Diesel (the so-called Lower Heating Value) being 36 MJ/L or 9975 Wh/L. The better the efficiency of the vehicle, the lower will be the CO_2 emissions for each km driven. Then, the emissions for a given trip will be calculated simply by multiplying the specific emissions of Diesel fuel (in gCO_2/kWh) by the energy spent during that trip (in Wh) [21].

Transmission

Most Electric cars have a fixed transmission relation, since electric motors have high torque even at zero speeds. ICE cars, on the contrary, need a multi-speed transmission. Nevertheless, the use of a multi speed gearbox in EVs might be useful to reduce energy loss due to high motor speed and to obtain a torque range which is more flexible. For instance, a small motor should use high reduction ratios to enable an acceptable starting torque. However, this would reduce the vehicle’s top speed. Overall transmission efficiency is normally quite high, around 98% [21].

Approach of this Chapter

There are several factors which affect the overall efficiency of vehicles. Official consumption figures are often made for unreal driving schedules such as the NEDC. Also, OEMs do not frequently disclose a lot of important information that is needed for suitably evaluating the consumption performance of vehicles. Therefore, this chapter tries to address this lack of knowledge concerning real world driving. Two similar car models with Diesel and full electric powertrain have been carefully monitored during charging and for a set of driving conditions / schedules. Consumption figures have been compared and discussed.

VEHICLES

There are already some electrified vehicles available in the market. Parallel hybrids such as the Toyota Prius or Series Hybrids (also called Extended Range Electric Vehicles, EREVs) such as the Opel Ampera (Chevrolet Volt in the US). However, usually the name "electric vehicle" is used for the full Electric Vehicle (EV) and in this category there are already some mass produced cars such as the Nissan Leaf which already sold over 60,000 vehicles worldwide, or the sporty and exclusive Tesla Roadster. Particularly, one OEM (Renault) has a full range of electric cars called ZE (Zero Emmission), ranging from the small Twizy to the commercial Kangoo. In the segment of family cars there is also the Zoe and the Fluence ZE. This latter model was the one chosen for this work, having been kindly provided by Renault Portugal, which also supplied a diesel (ICE) car with similar characteristics (Renault Megane).

The characteristics of both the Electric and ICE cars are presented in Table 1. The EV is longer than the ICE car, so as to compensate the extra space needed for batteries in the boot space. The philosophy of Renault is somehow different from the other manufacturers who distribute the batteries throughout the car in order to optimize space. Renault has interchangeable batteries, which means that the batteries have to be packed in a "box" that should be easily replaced by a system like the one proposed by the Company BetterPlace. The batteries are placed between the rear seats and the boot, "robbing" a significant boot space.

Table 1. Characteristics of the EV and ICE Car

Characteristics	**EV**	**ICE (diesel) Car**
Vehicle mass (kg)	1605	1307
Dimensions (mm)	4748x2041x1458	4559x1804x1469
Engine Type	Synchronous Motor Rotor Winding	Turbocharged Diesel common-rail
Power (kW)	70	77
Gear Box	Direct drive (1 speed)	6 speed
Storage Energy Type	Lithium-ion battery	Diesel fuel
Stored Energy (kWh)	22	701.4
Range (km)	185	1363 (combined)
Maximum Speed (km/h)	135	190
Acceleration 0-100 km/h (s)	13.7	11.9
Rated Fuel consumption (L/100 km)	-	4.5
Rated Carbon dioxide emissions (g/km)	-	120

Comparing both cars, the electric has a much higher weight (23%) as a result of the added weight of the batteries and has less power (10%). Therefore it is not surprising that it is a slower vehicle, both in maximum speed and in acceleration, as seen in Table 1. But there is another reason for these differences. The EV has only one gear while the ICE car has a 6-speed gear-box. Although the torque of an ICE is much lower than the torque of an electric motor with similar power, having gears allows it to accelerate faster (in 1st and 2nd gears) and to reach higher speeds (in 5th or 6th). But the largest difference between the vehicles is in terms of the energy that can be stored in each of them, which is 30 times higher on the ICE car, but leading only to 7.4 times higher range (an indication of the lower efficiency of the Diesel powertrain). The stored energy and ultimately the range is still the Achilles heel of EVs and the Renault Fluence ZE is no exception. In fact, we never saw a predicted range of more than 110 km, and that happened during the slow trips (80 and 90 km/h).

TESTS

Road Tests

Three types of energy consumption tests were performed, all of them at constant speed. One test typology consisted of horizontal short distance trips (2 km) carried out for a broad range of fixed speeds (40 – 120 km/h). Another test typology was a long distance round trip (around 120 km total) made mainly on motorways, with intermediate recharging (prior to the return trip) and made for a more limited constant speed range (80 - 120 km/h). A last test typology was extracted from the long distance trips, consisting on the 6% up-hill sections of these trips, analyzed separately. Not all the tests were possible to perform with both vehicle types.

The speed was kept constant by activating the cruise control of the vehicles. Measurements of average power supplied to the motor controller (kW), as well as total energy supplied to the powertrain for the whole test (kWh/100 km) were recorded for the EV.

Average power for each test was calculated not only from the instantaneous power measurements but also from the total trip energy consumption. This parameter was converted into average trip power. Therefore, the average power plots were obtained from an average of the power and energy measurements in order to decrease the error.

For the ICE car the cumulative fuel consumption (L/100 km) was recorded for each test. To allow the comparison of the ICE and the electric powertrains, the power and energy supplied to the ICE powertrain were calculated from the fuel consumption. This was made by calculating the thermal energy (power) associated with the mass (mass flow rate) of fuel supplied using the Lower Heating Value (43 MJ/kg 0.835 kg/L) of the diesel fuel. Therefore, the energy (power) used in this work for the ICE car corresponds to the energy (power) released by the fuel (only a fraction will effectively be converted into useful work or power). In order to control the fuel consumption of the vehicle, its tank was fully filled with fuel before and after each round trip.

Battery Charging Monitoring

The battery charging process was monitored with a FLUKE 435 Power Quality Analyzer. This equipment was programmed to register every 1 minute the main parameters related to the battery charging process, such as the RMS values of the power grid voltage and current, the absorbed active power and the energy consumed during the battery charging process. To perform a complete analysis of the battery charging process other parameters were also recorded such as power grid voltage and current harmonics, frequency, and total power factor.

Fig. 1 shows the outline of the setup used to monitor the battery charging process. This figure also presents different parts inside the vehicle, as the on-board battery charger, the interconnection box and the batteries. As shown, the battery charger converts the power grid voltage from 230 V (AC) to 400 V (DC), and the interconnection box makes the connections between the battery charger and the batteries. Fig. 2 shows the setup used to monitor the battery charging process. In this figure the FLUKE 435 Power Quality Analyzer, the FLUKE current probe and the Electric Vehicle Supply Equipment (EVSE) of the Renault Fluence ZE can be seen.

To charge the batteries the EV was plugged to the power grid using a Type 1 (SAE J1772-2009) connection of the international standard IEC 62196. When charging the vehicle from domestic electric sockets, it is necessary to use an EVSE cable because of the charging mode 3 used in this international standard. This mode is used in single-phase systems with maximum allowed voltage of 250 V (AC) and maximum allowed current of 32 A (80 A in the United States).

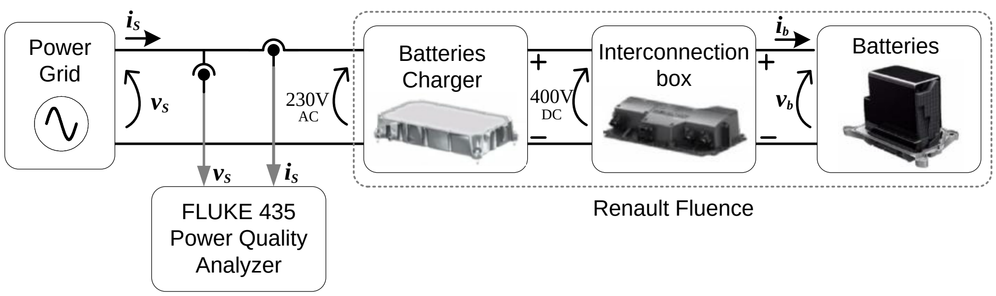


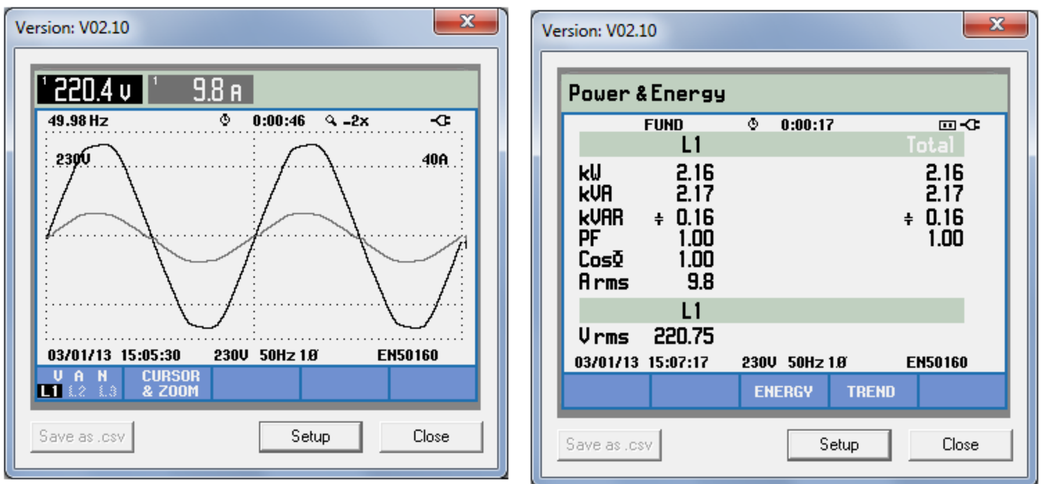
Fig. 1. Outline of the setup used to monitor the battery charging process.

Fig. 3 shows the results during a random battery charging process. Namely, Fig. 3 (a) displays the power grid voltage and current, while the measured powers (active, apparent and reactive powers), the power factor and the RMS values of current and voltage are shown in Fig. 3 (b).

Fig. 2. Setup used for monitoring the battery charging process.

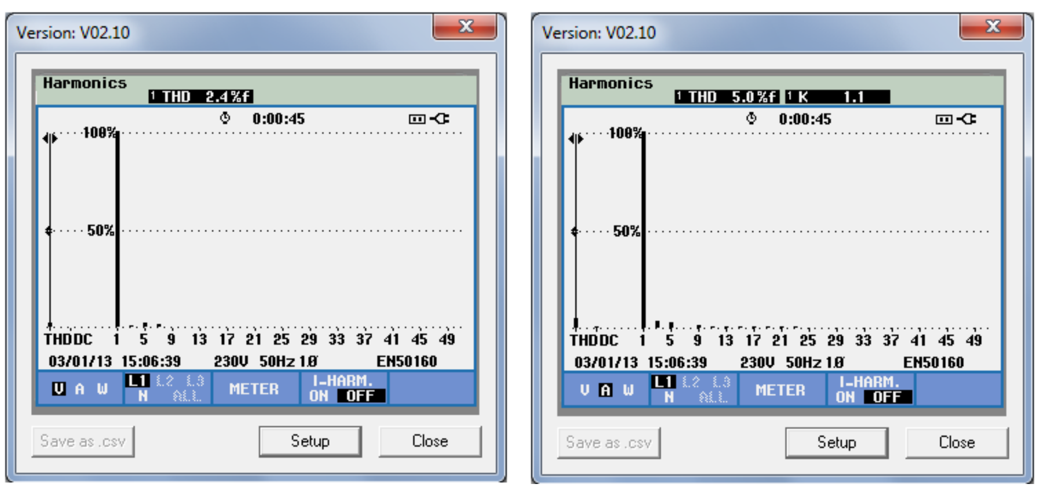
Fig. 4 presents the spectral analysis and the Total Harmonic Distortion (THD) of the power grid voltage (a) and consumed current (b) for a typical test. During the battery charging process the power factor was unitary and the consumed current presented a small distortion with a THD of 5%. The power grid voltage presented a THD of 2.4% as a result of the other non-linear loads connected to the power grid.

In this context, considering the predictable proliferation of EVs [23], it is extremely important to regulate the battery charging process [24][25] in order to preserve the power quality in the power grids [26][27][28]. The battery charging system of the Renault Fluence ZE accomplishes this objective, operating with unitary power factor and almost sinusoidal current consumption, although it only allows operation in unidirectional mode, denominated as Grid-to-Vehicle (G2V). In the future, smart grids will allow energy to flow in the opposite direction, allowing the concept of Vehicle-to-Grid (V2G), in which part of the energy stored in the batteries can be sent back to the power grid, helping to improve the power grid stability at certain periods [29][30][31][32].



(a) (b)

Fig. 3. Sample results for battery charging process: (a) Power grid voltage and current; (b) Measured power, power factor and RMS values.



(a) (b)

Fig. 4. Spectral analysis and THD during a typical battery charging process: (a) Power grid voltage; (b) Consumed current.

The battery charging was performed in two distinct places, in a private home and at a university. Fig. 5 presents the power grid voltage and consumed current profiles obtained during a typical test. It can be seen that due to the battery charging process, the power grid voltage in the house was affected and fell slightly but its value was kept within the 10% admissible fluctuation, as defined by the European standard EN 50160. Despite the voltage fall to a constant value, the current was kept almost constant at 10 A at nearly all the time, meaning that the batteries are charged with constant power. At the end of the battery charging process, during about 10 minutes, the consumed current is non-constant. During the battery charging process the power factor was also kept constant at with unitary value. No significant deviation from the nominal frequency was ever registered, which attests the good stability of the power grid.

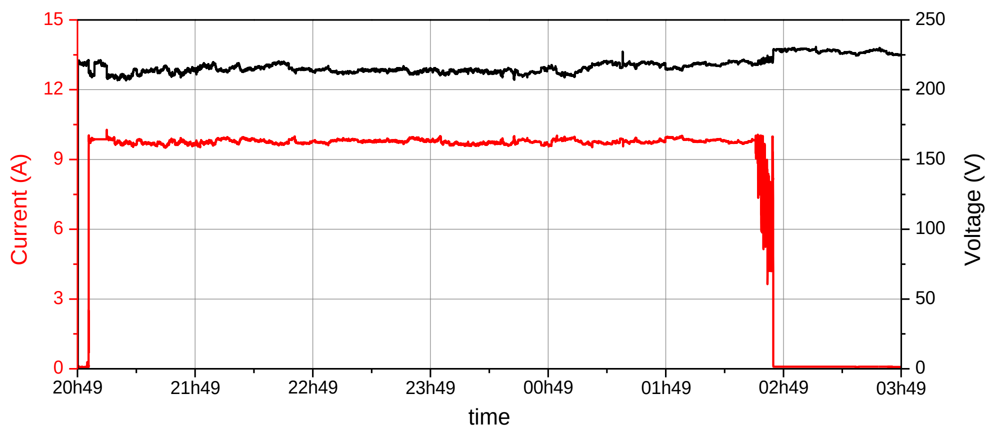


Fig. 5. Results recorded during a battery charging process at home.

The recorded energy values represent the energy that was supplied by the power grid to the EV, but do not represent the energy effectively stored in the batteries, as the charger and the batteries have a given energy efficiency. Typically, the battery charger efficiency is specified by the manufacturer and usually is defined as a function of the output power, which can change during the battery charging process. On the other hand, the battery charging efficiency is strongly influenced by several parameters, mainly their temperature, the ambient temperature, and the schedule of the charging, i.e., if the charging process is performed immediately after the discharging process or after a time delay. Typically [33], the efficiency of the battery charger and of the batteries is about 94% and 85%, respectively, so, only about 80% of the energy provided is effectively stored in the batteries [33]. Similar values for the overall charging efficiency are also reported by other authors [34], but based on slightly different efficiencies of battery charger and batteries (both around 90%).

RESULTS

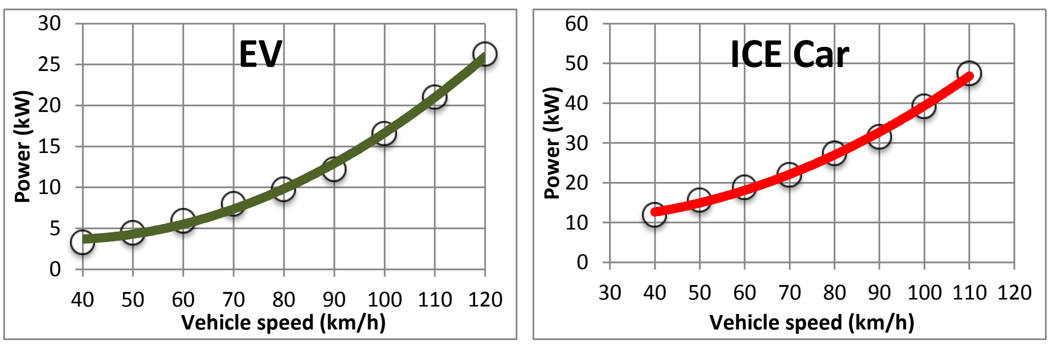
The energy and average power results presented may concern either used or charged energy/power. In the case of the EV, the used energy/power refers to the energy or the average power coming from the batteries, which was used to accomplish a given route (this includes consumption due to auxiliaries such as air conditioning). The charged energy refers to the total energy supplied by the electric grid to recharge the vehicle’s batteries back to 100% SOC after a given route. On the ICE car the charging efficiency is 100% so there is no difference between the used and the charged (supplied) energy/power. They refer to the thermal energy/power supplied by the fuel to the engine.

Short Distance, Constant Speed Tests

The tests at constant speed were performed on a horizontal stretch of dual carriageway with an extension of 1 km. They were done in both directions and repeated several times each. Speeds ranging from 40 to 110 km (to 120 km/h in the case of the EV), in increments of 10 km/h, were tested with both cars. The four results (sometimes 6 or 8 for each speed) were then averaged and plotted against vehicle speed.

Graphs for used power of the EV and ICE car can be seen in Fig. 6 (a) and (b), respectively. Both lines increase monotonically from 40 to 110 km/h. It can seen that the power curves fit quadratic trend lines. This agrees well with the fact that aerodynamic drag, lubricated contact drag (and in general viscous drag) also increase quadratically with speed.

Comparing Fig. 6**Ошибка! Источник ссылки не найден.** (a) and (b) it can be seen that the ICE (diesel engine) car needs roughly twice the power of the EV to perform the same task (note the factor of 2 between the axis' scales). Surely, the comparison is tricky, as the energy consumptions for producing and supplying electricity / Diesel fuels are not considered here. As already noted in the introduction, that would require a Well-to-Wheel (WTW) Life Cycle Analysis instead of the Tank-to-Wheel (TTW) approach here used. The WTW is out of the scope of this paper but has been used by the group for other works [17].



(a) (b)

Fig. 6. Average power consumption for short tests at constant speed with (a) EV and (b) with ICE car.

It is possible to see the same information but in terms of energy consumption in kWh/100 km (Fig. 7) for both vehicles. Please note that the increment of energy consumption with speed in each curve is now much lower than in the previous graphs, as the speed is not included in the energy as it is in the power calculation.

Fig. 8 shows the normalized power consumption using as reference the power for the 110 km/h (maximum tested speed) test. It can be seen that for the EV the ratio of required power between lower (40 km/h) and higher (at 110 km/h) speeds is 0.16, whereas in the ICE car this ratio is 0.25 (Fig. 8). This shows that the electric motor is more apt for running at lower speeds with fewer losses. One of the problems with the ICE car is that below 70 km/h

6th gear could no longer be used. This affects mechanical losses as a higher engine / wheel rotational speed ratio will be present below 70 km.

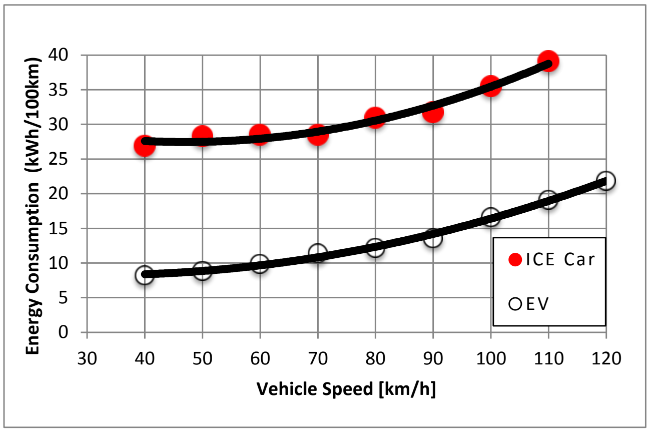


Fig. 7. Energy consumption for short tests at constant speed with EV and ICE car.

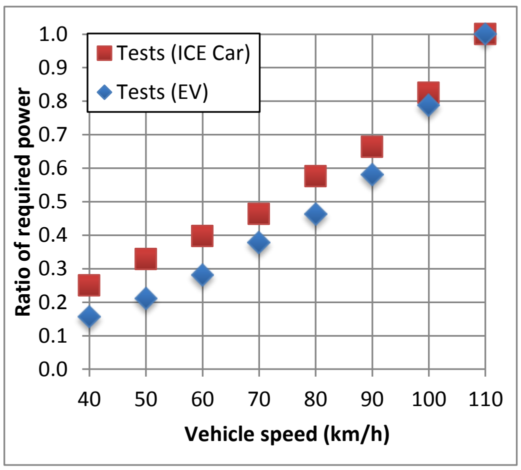


Fig. 8. Power required for maintaining speed, as a relation to 110 km/h.

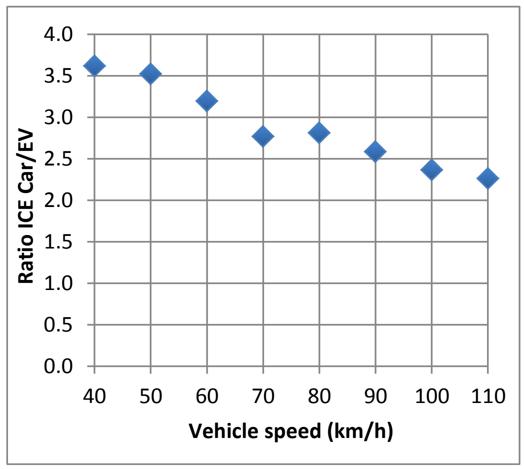


Fig. 9. Ratio of energy consumption between ICE car and EV.

When comparing the energy consumption on both vehicles, the Diesel consumption was always at least 2-fold higher than the consumption of the EV (Fig. 9). However, the ratio increased as the speed decreased, showing the reduced capability of the ICE to cope with low speeds efficiently.

Long Trip, Constant Speed Tests

The long trip tests were performed between the cities of Guimaraes and Vila Nova de Gaia (Fig. 10) both ways, with a total of more than 120 km. The overall distance was run on dual carriageways, with most of it being done in motorways. However, it was not possible to maintain the speed setpoint for all the distance (Fig. 11), because of motorways interchanges (km 27 and 95), toll booths (km 7, 52, 68 and 113) and in the approaches to the cities (start, middle and end). But, as it can be seen in Fig. 11, most of the trip was carried out at the speed setpoint. When in the motorway, the cruise control of the car was set to the required speed for all the distance. The small "wrinkles" seen in the trip are a result of the GPS reading, as the cars were controlled (by their cruise control) within ±2 km/h of the setpoint.

An histogram of the speed data points can be seen in Fig. 12. Almost 80% of the overall distance was travelled at speeds between 97.5 and 102.5 km/h, showing that most of the trip was in the vicinity of 100 km/h.

The road is somehow hilly, with altitudes ranging from 50 to 250 m (Fig. 13). The figure shows the return trip (Guimaraes-Gaia-Guimaraes), which, as it can be seen, is symmetrical.

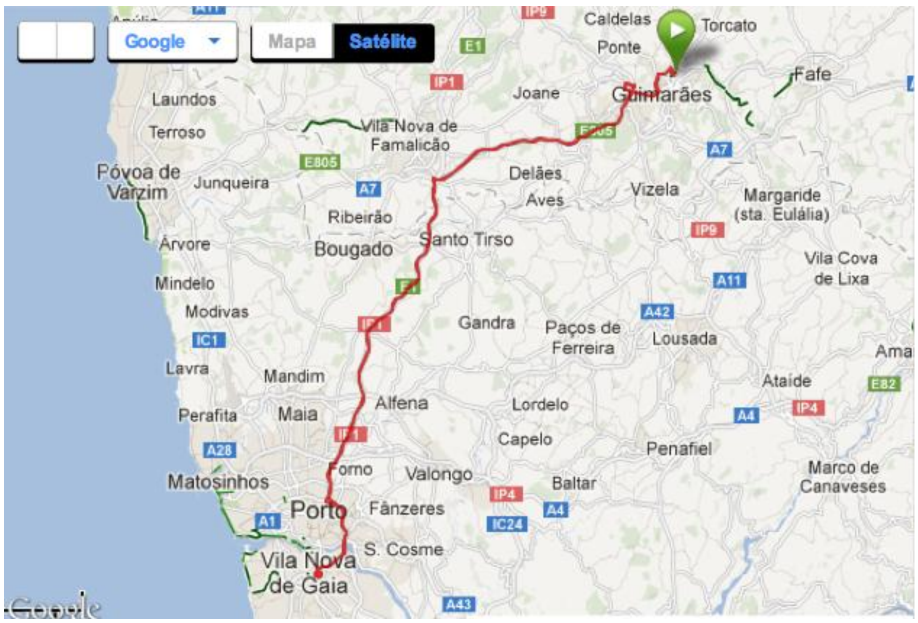


Fig. 10. Road trip (return).

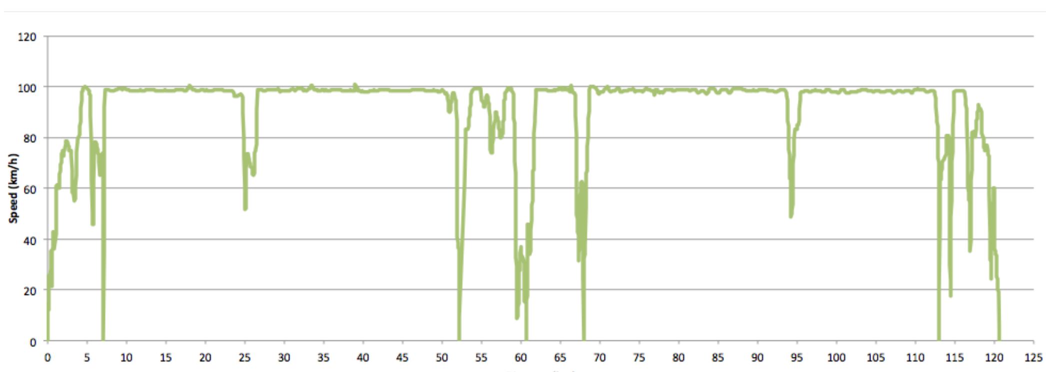


Fig. 11. Speed of the round road trip against distance (100 km/h).

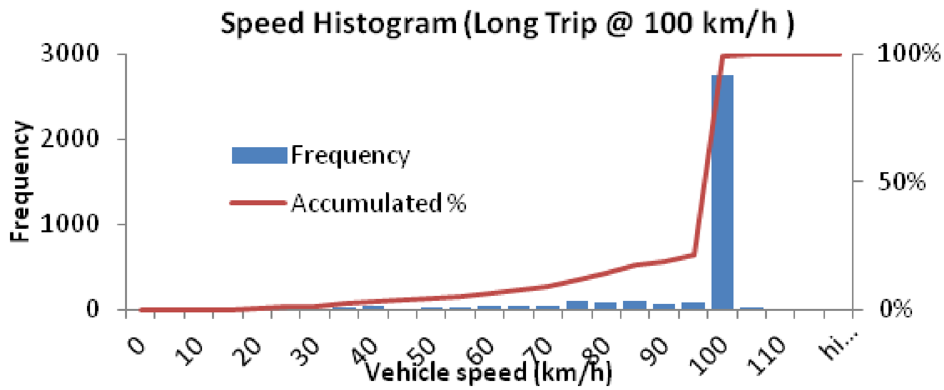


Fig. 12. Histogram for speed of the round road trip against distance (100 km/h).

Fig. 13. Altitude of the road trip.

Only 3 speeds were evaluated (90, 100 and 110 km/h) for the ICE car, but for the EV speeds of 80 and 120 km/h were also tested. Speeds lower than 80 km/h are extremely slow for a motorway and speeds higher than 120 km/h are not legal (the legal limit in motorway in Portugal is 120 km/h).

The results are shown in Fig. 14 for the Electric and for the Diesel powered cars. The values are an average of the energy consumption of the car, in terms of average power (in kW) in electricity and in Diesel fuel. As it can be seen, in terms of energy, the ICE car uses more than twice as much energy as the EV (Fig. 15). These values, although different, are in line with the results for the short distance tests (Fig. 9).

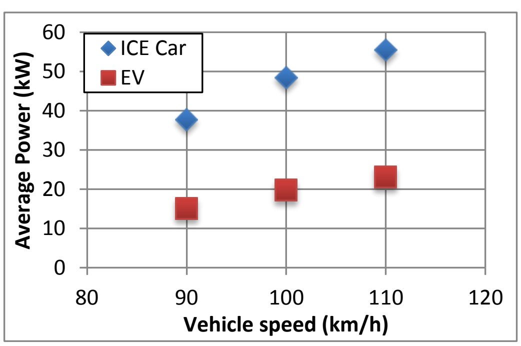


Fig. 14. Average power for the long trip.

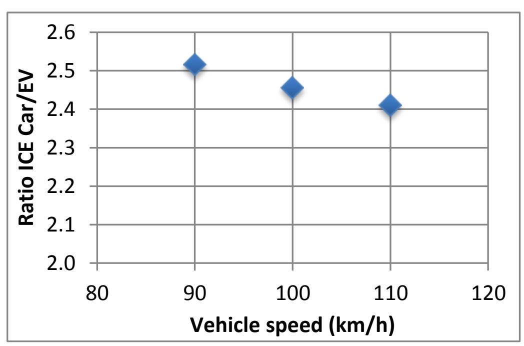


Fig. 15. Relation of energy consumption (Diesel / Electric).

When plotting the data for short vs long tests (Fig. 16 and Fig. 17), as it would be expected, the values for the long trip are somehow higher, reflecting the altitude and level changes during the long trip, inexistent in the short tests.

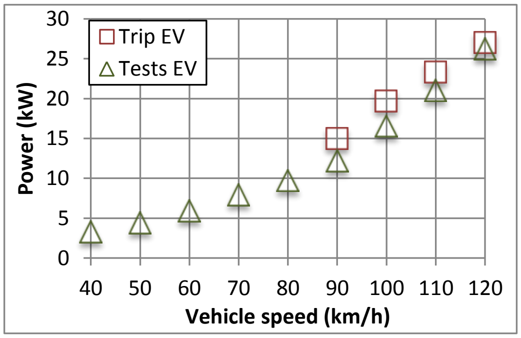


Fig. 16. Average power for the short & long trip (EV).

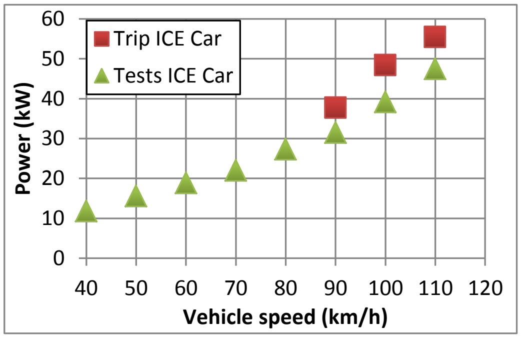


Fig. 17. Average power for the short & long trip (ICE car).

Steady Up-Hill Tests

During the long trips the values for maximum consumption during the steepest sections of the road (6% gradient) were recorded and plotted (Fig. 18 and Fig. 19) for the EV and for the ICE car, respectively. In the figures, these values are plotted with the average consumption during the overall trip, for comparison. Note again the factor of 2 between the vertical axes of both plots.

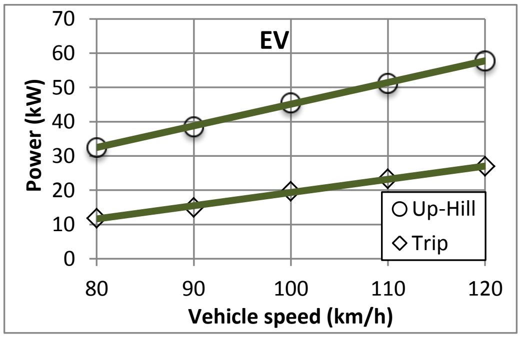


Fig. 18. Road trips with EV (average and required power for up-hill).

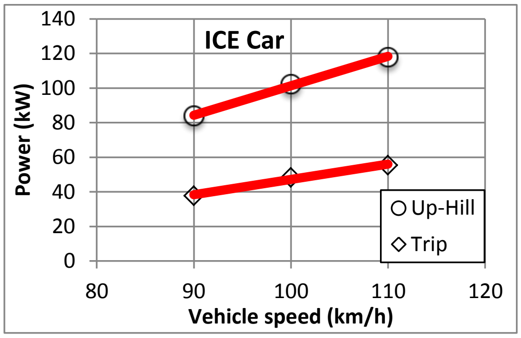


Fig. 19. Road trips with ICE car (average and required power for up-hill).

Like for the previous results, Fig. 20 shows the difference for energy consumption between both vehicles in the up-hill sections. Again, the ratios are above 2, although lower than in the case for the leveled tests (Fig. 9) and for the long trip tests (Fig. 15). As the vehicle required power is higher for this up-hill test, the efficiency of the ICE is here somehow higher than on the other conditions. This again proves the higher difference in efficiency between EV and ICE cars during low power requirements.

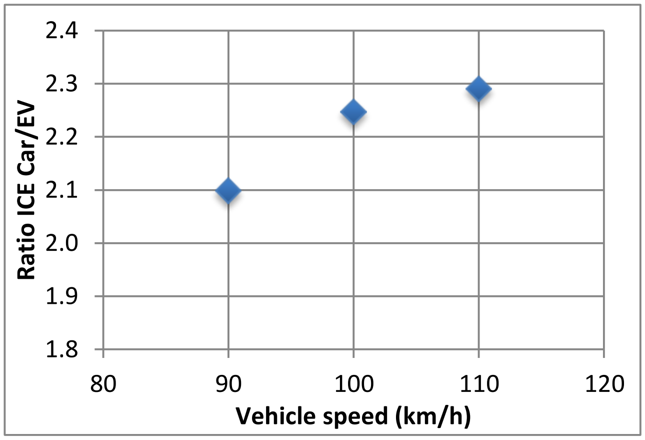


Fig. 20. Relation of energy consumption (ICE Car / EV).

The overall results are summarized in Fig. 21 and Fig. 22 for the EV and for the ICE car, respectively, and for both cars in Fig. 23.

When comparing the power used in both cars as a ratio for all the tested conditions (Fig. 24), the ICE car almost always spends more than twice as much as the EV. However, this ratio is dependent on vehicle speed. For tests at constant speed in leveled ground the difference increases as the speed decreases. This shows the lower efficiency of the ICE towards low loads and specially using lower gear-box ratios. The electric motor is much more efficient, as its efficiency does not plunge as much as with the thermal engine but mainly because it uses the same ratio for its entire speed range. When the comparison is for higher power levels (up-hill), the difference is lower, showing the improved efficiency of the thermal engine as the load increases.

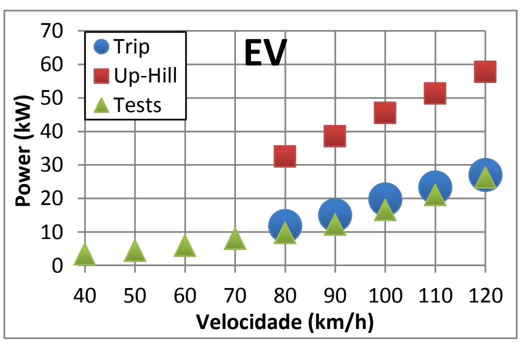


Fig. 21. Various required power for EV.

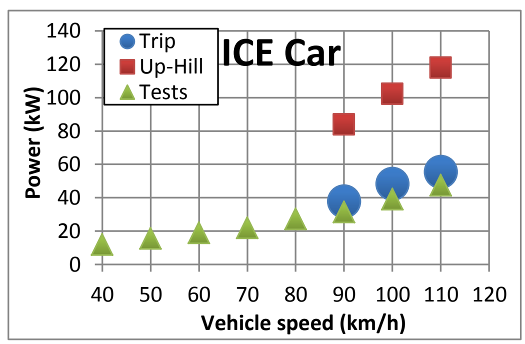


Fig. 22. Various required power for ICE car.

Electric Vehicle Charging

The data presented above was for the energy "spent" for the locomotion, by the electric motor and controller in the case of the EV or by the diesel engine in the case of the ICE car. However, there is an efficiency for the electric charger and for the batteries during charging and discharging processes. In this chapter, it was assumed that the ICE car had no inefficiencies of such kind, which is to say, that none of the diesel fuel supplied to the vehicle tank was "lost" during operation, as all the fuel delivered by the pump is effectively delivered to the ICE and burned in it.

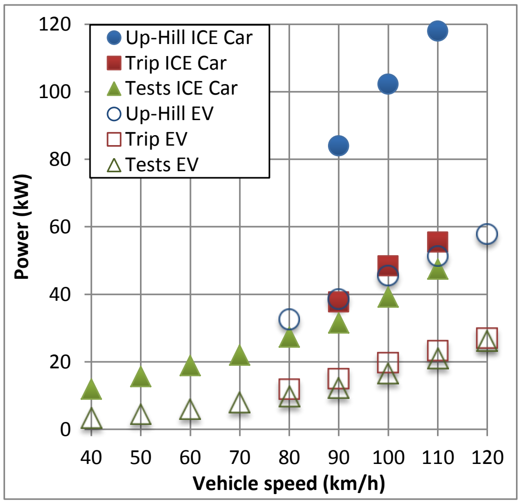


Fig. 23. Comparison between required power between EV and ICE cars (in kWh/100 km).

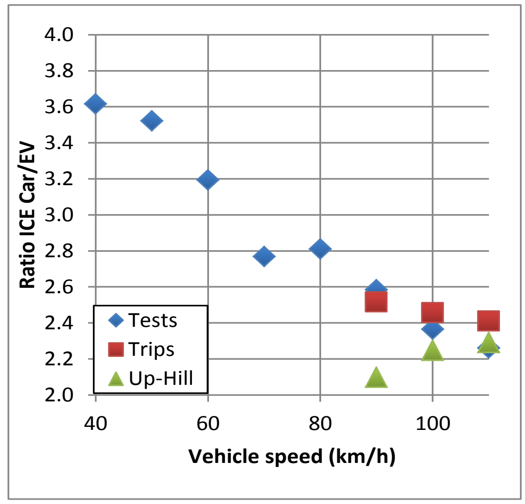


Fig. 24. Ratio for power required in ICE and EV cars for the same conditions.

The long trip presented earlier in this paper (Fig. 10) is composed of two stages, departing (outward) from Guimaraes to Gaia and returning (inward) from Gaia to Guimaraes. As it can be seen in Fig. 13, Guimaraes has an altitude of 200 m and Gaia (middle of the trip) an altitude of around 50 m. Therefore the "outward" trip has a lower consumption (for the same speed) than the "inward" trip (Fig. 25, for the EV). The difference between outward and inward consumption is roughly 20% higher for the trip returning to Guimaraes.

Before and after each stage of the trip the car was recharged to full SOC of the batteries and the energy supplied by the grid was measured.

It was possible to compare the charged (supplied) energy with the used (spent) energy for each of the trips' stages, which is plotted in Fig. 25. The efficiency of the system (charger+battery) is displayed on Fig. 26 showing the losses due to the operation of the charger and of the charging + discharging process in the battery.

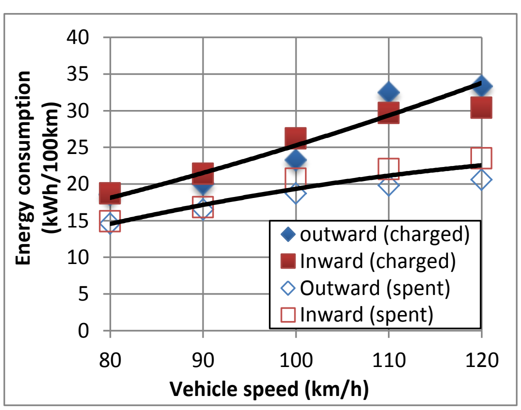


Fig. 25. Energy spent during the trips and energy charged for those trips.

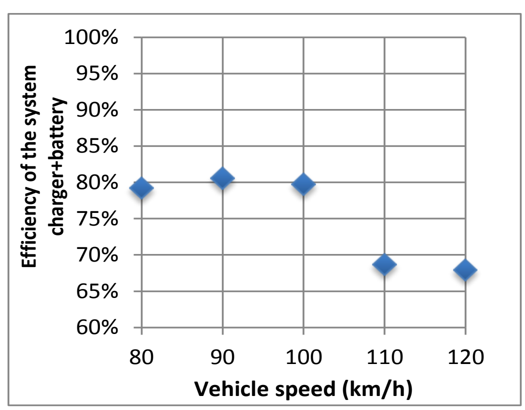


Fig. 26. Efficiency of the charger-battery system.

Strangely in Fig. 25, the values for energies charged for the outward trip at 110 and 120 km/h were higher than the values for the inward trips, although the energy spent for the inward trips was higher than that for the outward trips. It can be seen that the efficiencies of the charger-battery system corresponding to the outward trips at 110 and 120 km/h (which measured the energy for that trip) were much lower than those of the other tests. For the charging events for speeds up to 100 km/h, the charged energy was on average 25% in excess of the energy spent during the trip. For the outward trip at 110 km/h the charged energy was a massive 47% higher than the energy spent, showing the high level of energy lost with the discharging and subsequent charging of hot batteries.

With one exception, all the aforementioned charging events took place with the cooling fan running. As these results were peculiar, the return trips at 110 and 120 km/h were repeated, but the results were similar. Surely the differences may not be due solely to the energy required for the operation of the cooling fan, even if it operated for several hours. In fact, this continuous operation of the cooling fan indicates that the batteries were hot, due to the high power requirement of those trips which heated the batteries up to a high temperature. At this higher temperature both the charging and the discharging efficiencies are probably worse. And if efficiency is lower, more energy will be lost as heat. This heat will further hinder the cooling of the batteries creating a loop and therefore preventing the system of ever achieving normal optimized operation. If confirmed, this behaviour would recommend the instalation of a more powerful battery cooling system.

The overall result for energy consumption for both cars can be seen in Fig. 27. The ratio between the energy supplied to the EV (electricity charged) vs the energy supplied by the fuel to the ICE car ranged between 0.49 and 0.61 for the 90 km/h to 110 km/h range (Fig. 28).

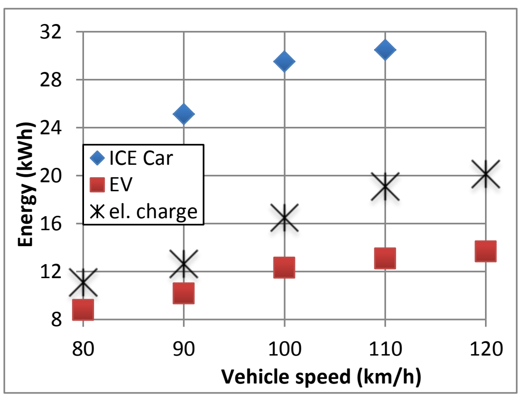


Fig. 27. Energy spent in EV and ICE cars, compared with electricity charged on EV.

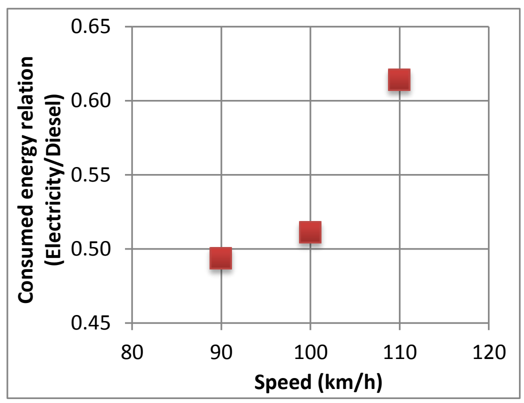


Fig. 28. Relation between energy charged to the EV and the energy supplied in Diesel fuel.

CONCLUSIONS

As it was noticed that there is currently a lack of real life comparisons between the energy consumption of Electric Vehicles (EV) and Internal Combustion Engine (ICE) cars, a test program to assess this issue was envisaged and completed.

Short distance tests at levelled ground and 6% up-hill road as well as long trips were done for a broad range of fixed speeds. Measurements enabling the assessment of average energy consumption and required power were performed for both vehicles.

It was found that the electric powertrain presented much higher efficiency than the ICE (diesel engine) but the difference was reduced as the average speed and required power (e.g., at up-hill sections) increased. The ratio of ICE to EV power requirement varied between 2.1 (up-hill test) and 3.6 (minimum speed tested).

When considering total energy supplied to the EV the value was on average 25% higher than the energy supplied to the electric motor for most speeds (up to 100 km/h). For higher speeds (110 and 120 km/h) this ratio increased to 47%. Under these high speed conditions the higher required power caused the increase of battery temperature, which eventually reduced the discharging efficiency and probably also the subsequent charging efficiency.

Overall, the energy supplied by the electric grid to the EV ranged between 49% and 61% of the energy supplied by the fuel to the ICE (diesel) car for identical trips.

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