ENERGY ANALYSIS OF AN ELECTRIC MINIBUS IN REAL CONDITIONS

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SOMMARIO

The objective of this study has been to analyze the energy flows and evaluate the overall performance under real conditions of the system " electric minibus", with particular reference to an application case of public transport. The analyzed vehicle is 5,3 m length of and 2,1 m width and it can carry 28 passengers maximum. The traction is guaranteed by a Direct Current (DC) electric motor with a power of 25 kW at 72 V, with a maximum torque of 235 Nm. The energy required by the engine is provided by two nickel-cadmium battery packs connected in series and having 125 Ah total capacity, with a nominal overall voltage of 72 V. The power output is modulated by the chopper, which controls the energy flow between the batteries and the motor. To perform the energy analysis, together with the on-board electronic diagnostic and monitoring systems installed by the vehicle manufacturer, an additional measurement chain has been used. The preliminary tests have been carried out on the vehicle to monitor the characteristic parameters: current and voltage of the batteries, vehicle speed.

Through the study of the obtained values, the vehicle energy performance has been analyzed in dynamic and real conditions, with particular reference to the following quantities: energy consumption per km in urban areas, overall efficiency of the system, maximum speed, charging time.

The first four variables have been evaluated under different load conditions (people that get on the bus and increasing the total vehicle mass) and routes (slopes), so that energy consumption of the vehicle can be evaluated in real drive cycles.

INTRODUCTION

As known, the goal fixed by Kyoto Protocol is to achieve stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. The transport sector emissions is about 32% percent on total emission [1-3]. To reduce this last value, a solution could be to use electric vehicles to improve the well to wheel energy efficiency. In fact compared to internal combustion engine vehicles, electric vehicles actually could use less energy and emit less carbon dioxide [4] so they are more efficient and sustainable than other conventional solutions. In addition, the energy in the powertrain could be provided by renewable sources.

The advantages of the electric engine can be summarized as follows:

- Locally emission free;
- More efficient transmission energy;
- No vibration during operation;
- Much longer life time;
- Recovery of braking energy;
- No traction energy losses during idle operation.

Most of the vehicle manufacturers either have developed electric technology in hybrid electric vehicle (HEV) and in hydrogen Fuel Cells powertrain [5]. In this scenario a key role is the public transport and in particular way the bus transport performed inside the city because it reduces emissions locally. In fact many studies have provided solutions to optimize hybrid electric buses, because it is typically characterized by better fuel utilization and lower emissions than comparable conventional buses [6-7]. An interesting project has carried out by Reinhart Kuhne that has demonstrated under which conditions the electric bus traction is more convenient than diesel bus [8]. In particular the hybrid vehicles have the advantage to obtain a higher powertrain energy efficiency by recovering energy loss during braking and deceleration phase [9].

DESCRIPTION AND METHOLOGY

As an example of electric vehicle, this paper has studied the energy efficiency and consumption of an electric minibus Gulliver U520ESP made by Tecnobus, which is currently used in Italy, France, Portugal and Great Britain. In Table 1, the powertrain characteristics have been reported.

Table 1 – Powertrain characteristic

Energy storage	Nickel-Cadmic Batteries, 72 V, 125 Ah
Vehicle speed	30 km/h
Max Power	27 kW
Electric engine	25 kW, 72 V, 235 Nm
Bus weight	6000 kg

The minibus tests have been performed in real conditions, taking into account a reference route for the several experiments and varying the weight loaded, by varying the number of passenger. The reference pathway is from the touristic port to the city center of Civitavecchia as shown in **Errore. L'origine riferimento non è stata trovata.**. The total covered distance is about 1,6 km. The work was carried out to evaluate the bus behavior inside a city in the stretches of the road with different characteristics. The primary aims have been to calculate the energy consumption per km in urban areas and the total energetic efficiency of the system.

The reference pathway has been divided into four stretches to evidence the bus behavior in different slope working conditions: A-B, B-C , C-B e B-A. In fact, the part from A to B is descent; both from B to C and from C to B are flat land; the last part from B to A is an ascent road at 20%.

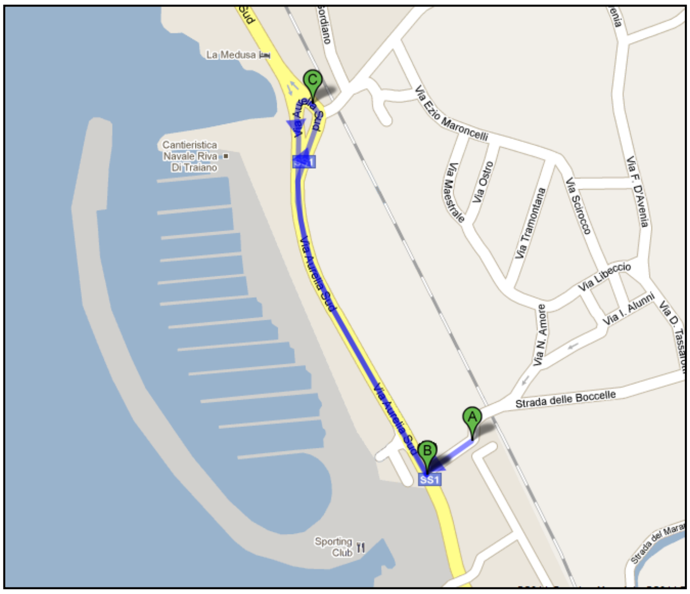

Figure 1 Reference test route in Civitavecchia city

The data acquisition system, used for monitoring the performance of the bus, has been chosen on the basis of bus operation features and of the electronic board system. The data acquisition devices consists of three NI field point modules, an USB-CAN Peak port and a serial port. The three national instruments modules of the field point have been connected to the computer to acquire the voltages and the currents directly from the battery package and the auxiliary battery.

The voltage of the batteries package has been split in order to extrapolate a fraction voltage, to match the field point working range (0-10 volts). The sample time has been set at 100 ms. The bus speed, the motor voltage and current data is acquired by the Tecnobus program through the serial port connected also to to the display to show those data to the driver. The field point data and the CAN data have been acquired through a Labview program. The CAN port (id standard and bound rate of 500Kbit/sec) has been connected to the bus monitoring system and the acquired data has been analyzed and compared with field point data to avoid errors. Afterwards the data has been processed to report it at the same base time line.

In order to create the same conditions in all the trials carried out, the battery were completely recharged before the beginning of all the tests.

The tests have been performed tackling the routes with different mass loads of 3, 5, 7, 10, 15 people and the different performances have been evaluated as the energy consumption per km in the urban area.

To complete the experiments, the recharge efficiency has been evaluated monitoring the battery recharge phase. The obtained values have been finally used to analyze the total cost of the provided energy and the kilometer energy cost

RESULTS

Through the electrical data acquired in different tests, the following values have been calculated:

- Energy consumption per kilometer in urban area;
- Mean traction power as a function of bus load;
- Recovered energy from braking in real driving cycle;
- Global system efficiency;
- Percentage of the inertial energy recovered against the bus load.

In Figure 2, the data of one test is reported. The graph references to the ten people load driving cycle. The maximum current delivered by the battery pack is about 510 A which means almost 4C-rate. This current value is so high only either when the bus performs a significant speed change instantly or when the bus is driving a considerable steep stretch. In the recovery braking mode, 50 A is the maximum current provided to batteries. As highlighted in the graph, the energy recovery is recorded in the descent path (A-B), where the current is negative.

When there is a current peak, every cell of the battery could decrease the voltage at 1 Volt. As a consequence, the batteries are very stressed when they work in dynamic conditions. In addition, the average consumption has been calculated for a urban cycle in the considered path in Civitavecchia city.

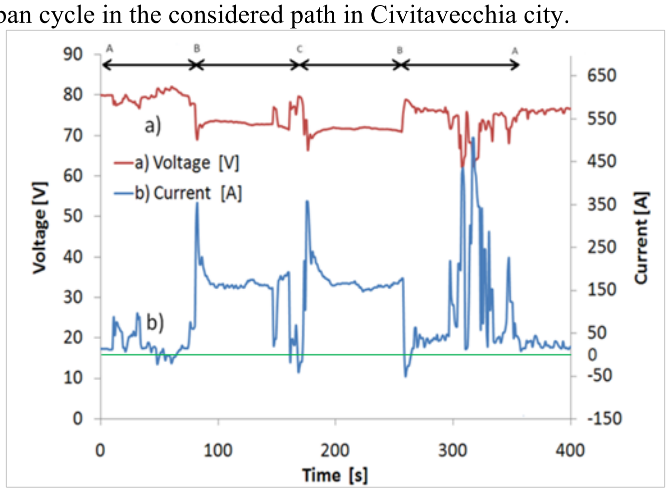

Figure 2 – Current and voltage profile during all path test

In the Figure 3, the power against the time is displayed. In the proposed case, loading 10 people, the total energy consumption has been 1,69 kWh, so the energy used per kilometer has been 0,53 kWh/km.

For every performed tests in this work, the graph in Figure 4 summarizes the specific traction energy versus the people number that is the total transport weight. Analyzing the carried out tests, the specific energy consumption has changed from 0,47 kWh/km to 0,55 kWh/km and varied linearly with the bus weight; in particular when the weight increases of 20%, the energy consumption increases of 20%.

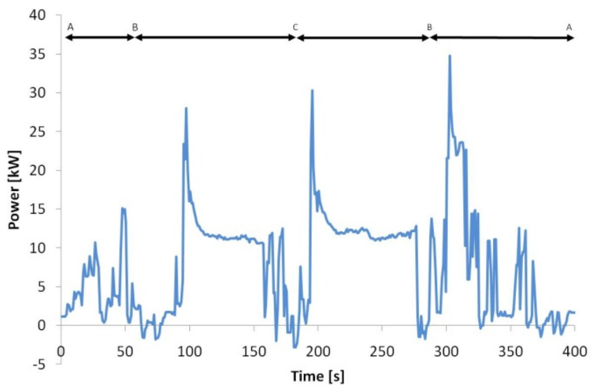

Figure 3 – Power trend for the 10 people load

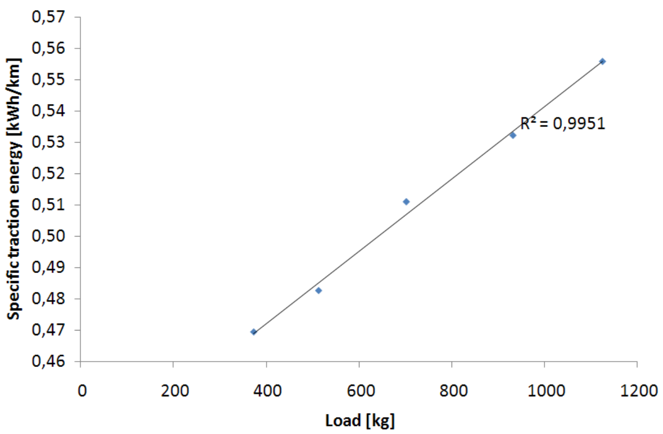

Figure 4 –Energy consumption versus the bus load

The average bus power has been calculated for different loads to evaluate their correlation. The acquired mean power has been between 6,6 kW and 8,7 kW as displayed in figure 5. The bus energy capacity is about 9 kWh. Therefore, the autonomy could vary from 1 hour and 20 minutes to about 1 hour for this drive cycle depending on the weight.

As the mean speed has been evaluated 10 Km/h, the corresponding range is respectively 10 km and 13 km.

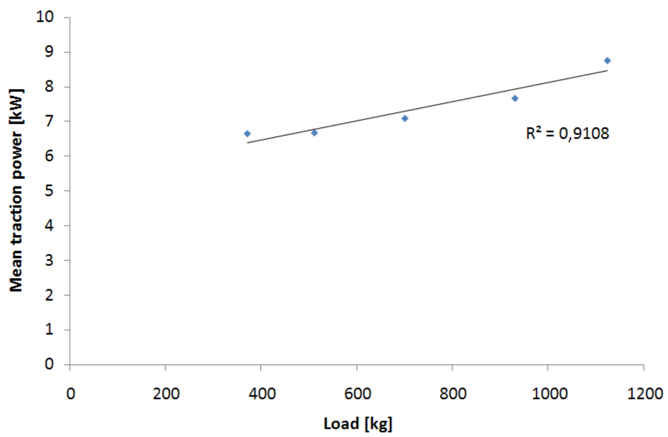

Figure 5 – Mean traction power versus the bus load

Comparing the figure 2 and the figure 6, it has been pointed out that the current is very high in correspondence of elevated acceleration of the bus. Analyzing the velocity in the Figure 6, the speed profile is specular respectively in AB-BA and BC-CB stretch, but the provided battery current and the power as wel as the consumed energy are bigger in the ascent stretch as showed in figures 2 and 3. In the flat path, the battery current has been near to C-rate, so that they were not particularly stressed except when high acceleration has been required and the bus has travelled around the maximum speed which has been equal to 33 km/h.

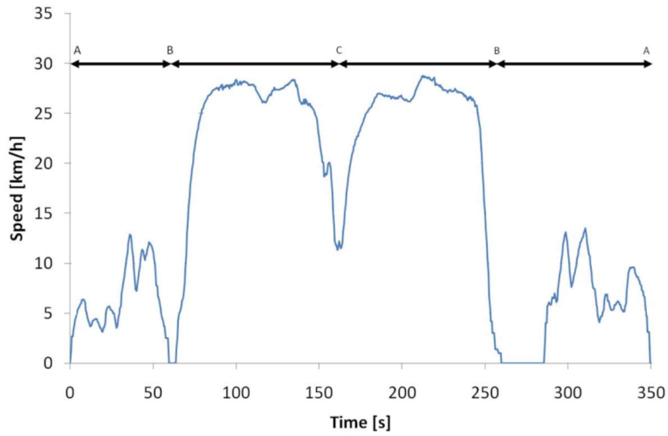

Figure 6 – Speed profile during half path test

Furthermore, considering the acquired data, the global efficiency parameter has been calculated. To calculate the global efficiency, the power at the wheels has been considered. This power, which is required for the vehicle specific mission, is the sum of four terms [10]:

$$P_w = P_{in} + P_{Tyre} + P_{aero} + P_{slope} \quad (1)$$

where:

P_{slope} is the power lost due to the inclination of the road;

$$P_{slope} = m \cdot g \cdot \sin\alpha \cdot v \quad (2)$$

The parameters are:

- m is the mass of the vehicle [kg];
- g is the gravity acceleration [m/s^2];
- α is the road inclination [rad];
- v is the speed [m/s].

The P_{slope} can be neglected in round cycles [10].

P_{in} is the power required to accelerate the vehicle:

$$P_{in} = m \cdot a \cdot v \quad (3)$$

where:

a is the acceleration;

P_{Tyre} is the resistance due to the tires equals to:

$$P_{Tyre} = m \cdot g \cdot f \cdot \cos\alpha \cdot v \quad (4)$$

Where f is the rolling coefficient defined as:

$$f = 0{,}013 + 6{,}5 \cdot 10^{-6} \cdot v^2 \quad (5)$$

The P_{aero} equals:

$$P_{aero} = \frac{1}{2} \cdot \rho_{air} \cdot C_x \cdot A \cdot v^3 \quad (6)$$

Where:

- ρ_{air} is the air density (~ 1,2 kg/m^3) at standard conditions;
- C_x is the drag coefficient;
- A is the frontal area of the vehicle [m^2].

Table 2 – Power at wheels

Power max [kW]	29.3	
P in [kW]	0.12	4 %
P tyre [kW]	2.64	90 %
P aero [kW]	0.17	6 %
Average Power [kW]	2.94	100 %

Once obtained the power at the wheels of the vehicle as a function of the time, the following considerations have been pointed out (Table 2):

1. The friction reduces the global efficiency in significant way. It is about 90% of the total energy needs;
2. The aerodynamic contrast energy is about 6% of the total energy needs;
3. The inertial energy is 4% of the total energy needs;
4. The calculated mean global efficiency is 60%.

Therefore, the 94% of the energy needs is directly connected to the mass and it is in accordance with the experimental data of the energy consumption as reported above in figure 4. The recovered brake energy increases proportionally to the total weight as well, as reported in Figure 8.

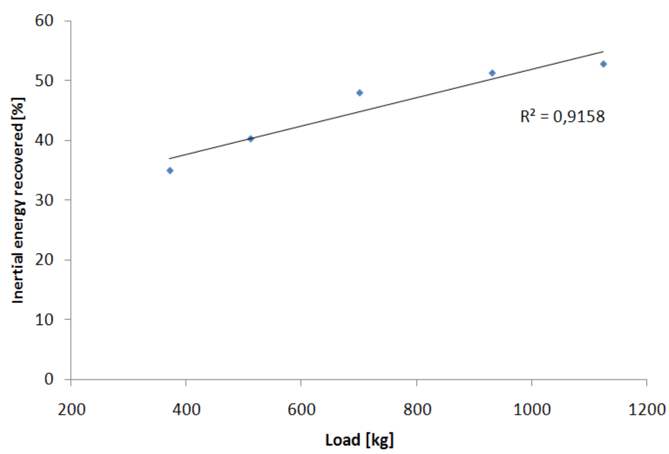

Figure 7 – Percentage of the inertial energy recovered against the bus load

Analyzing the graph, the brake recovery is very limited; in fact the value is 0,012 kWh on average during the reference round trip, but in comparison to the inertial energy, the recovered energy is up to 50% of the inertial one. It enhances proportionally to the total weight of the bus.

To complete the energy system analysis, the recharge phase has been monitored acquiring the current values during a recharge procedure. In the starting condition, the battery pack was so low that the bus could not be switched on.

Analyzing the current trend against the time, reported in figure 9, it was pointed out that the recharge profile has been set by the charger manufacturers in order to optimize the energy transfer and preserve the battery health.

Therefore the batteries have been charged at C/3 and C/6, which is a quite low current. In the case that the battery had been charged at either C or 1,5 C, the charging time would have been between 1 hour and 40 min. This recharge power would have been practicable by this kind of batteries. Referring to the Handbook of battery [11], charge efficiency has been estimated. It is defined as the ratio between the OCV and the charge voltage, it equals about 95% at low current while at higher current it could reach 89%.

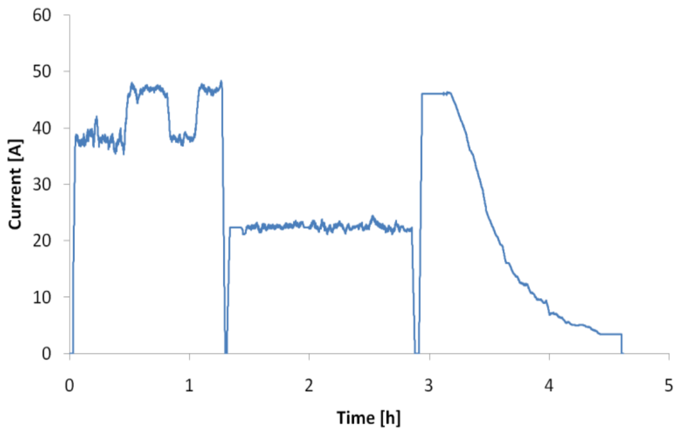

Figure 8 – Current values during recharge phase

All these tests have been performed utilizing the nichel-cadmio battery pack. This last technology has an energy density of 0,11 kWh/l (specific energy of 0,055 kWh/kg). Utilizing a different battery pack as lithium battery, with an energy density of 0,250 kWh/l (specific energy of 0,11 kWh/kg), fixed the volume, the bus autonomy could be doubled so that the range could reach about 20 km. In fact the condition will be the same with only 20 kg of weight difference.

Considering that the energy consumption can vary from 0,47 kWh/km to 0,55 kWh/km and that the recharge efficiency is 90%, it is possible to calculate the correspondent energy adsorbed from the grid and the total operating cost for each kilometer. Considering an average value, the energy required from the grid could be equal to about 0,59 kWh/km. Taken 0,15 €/kWh electric energy cost, the minibus energy cost per kilometer can be evaluated to be 0,08 €/km. For comparison, referring to a Diesel minibus by Ford, it could perform 12 km with a liter of fuel and considering 1,5 €/l the total cost per kilometer is 0,125 €/km, which is higher than the value evaluated for the electric bus.

In terms CO_2 emissions, the diesel minibus produces 250 g/km and consumes 0,94 kWh/km of primary energy. With regard to the electric minibus, considering the Italian electric energy mix with 80% fossil sources [12], than 300 g/km CO_2 are produced from the well to the wheel and the non renewable primary energy consumption is 1,26 kWh/km. With the same characteristics of the minibuses, to obtain the same emissions in both the cases, the Italian electric energy mix should be 67% of fossil sources primary energy.

CONCLUSIONS

The aim of this study has been to analyze the Minibus energy overall performance under real conditions with particular reference to an application case of public transport in a reference pathway in Civitavecchia, Italy. The most important energy quantities have been acquired by an on-board equipment and analyzed varying the people number and, as a consequence, the total transported weight.

The analysis demonstrated that enhancing the load from 300 to 1200 kg, the energy consumption vary from 0,47 to 0,55 kWh/km. Furthermore, it has been demonstrated that the highest power needs are due to the friction, counting the 90% of the energy consumption. Therefore it is recommended to use the high efficiency wheels. In addition, taken that the 94% of the energy needs depends on the total mass, the weight reduction could lead to a high improvement of the energy system efficiency, for example using lighter batteries and using hybrid FC powertrain. The inertial energy is about 4% of the total energy needs and it can be retrieved up to 50% by breaking recovery system. All these results may be used to estimate the effective range of an electric bus designed for the public service.

In addition, the battery has been electrochemically robust, because it could deliver up to 4C-rate current in correspondence to a cell voltage of 1V.

Moreover, by a comparison between the diesel and the considered electric minibus, this last has still too long recharging time, the operational cost of the electric minibus is lower than the conventional ones, but in terms of energy and CO2 emission, the conventional vehicle are still more convenient than the analyzed one.

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SUMMARY

L'obiettivo di questo studio è stato quello di analizzare e calcolare i flussi di energia e il rendimento globale in condizioni reali di un "minibus elettrico", con particolare riferimento al servizio per trasporto pubblico. Il veicolo analizzato è di 5,3 m di lunghezza e 2,1 m di larghezza e può trasportare 28 passeggeri al massimo. La trazione è garantita da motore elettrico a corrente continua (DC), con una potenza di 25 kW a 72 V, con una coppia massima di 235 Nm. L'energia richiesta dal motore è fornita da due stack di batterie al nichel-cadmio collegati in serie e aventi 125 Ah di capacità totale, con una tensione nominale complessiva di 72 V. La potenza è modulata da un chopper, che controlla il flusso di energia tra la batterie e il motore. Per eseguire l'analisi energetica, è stata usata, insieme ad un sistema di diagnostica e monitoraggio installato bordo dal costruttore del veicolo, una catena di misura aggiuntiva. I test preliminari sono stati effettuati sul veicolo per monitorare i parametri caratteristici: corrente e tensione delle batterie, velocità del veicolo.

Attraverso lo studio dei valori ottenuti, sono state analizzate le prestazioni energetiche del veicolo con particolare riferimento ai seguenti quantitativi: il consumo energetico per km nelle aree urbane, l'efficienza complessiva del sistema, velocità massima, tempo di ricarica.

Le prime quattro variabili sono state valutate in differenti condizioni di carico (passeggeri e massa del veicolo) e percorsi (pendenze), in modo da poter valutare il consumo energetico del veicolo in un ciclo di marcia reale.