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ELECTRIC BUSES FOR URBAN TRANSPORTATION: ASSESSMENTS ON COST, INFRASTRUCTURE AND EXPLOITATION

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Abstract**—**Urban transport is one of the most challenging sectors of the public administration of a metropolitan area. Fuel cost, maintenance, transport capacity, pollution represent only a small amount of the data that is taken into consideration in the decision of purchasing a new fleet of urban buses for public transport.

Electrification of the public transport is not a new solution; there is the tram, the trolleybus. Is there going to be a place for the electric bus taking into consideration the purchasing cost of the bus, the battery need to be replaced, the weight of the bus, the charging infrastructure, the limitations of the bus due to the range of no more than 150 (km), battery charging time and road gradient. It is possible that these limitations overcome the benefit of zero local emissions, reduced cost of exploitation, and almost no maintenance of the power-train, all of them being immediate benefits of the electric buses use as a solution in urban transportation environment.

Keywords**—**Cruise, TruckMaker, electric bus, energy efficiency, pollutant emissions.

I. INTRODUCTION

AS the number of motor vehicles grows, the problems of traffic agglomeration in the urban environment and of the deterioration of the air quality, that the large cities are faced with, are becoming increasingly stringent. Thus, the tendencies are of taking immediate measures for improving the quality of life in the large cities, in order to preserve the environment and the human ecosystem [1].

The classic buses that are in use in the urban traffic do not comply with the increasingly strict criteria that are to be met, namely: reducing the noise levels and improving the air quality, according to the obligations imposed by the EU-directives; reducing the CO_2-emissions produced by classic buses due to the internal combustion engines; reducing the exploitation of conventional energy resources obtained from fossil fuels [2, 3].

The replacement of the buses with classic Diesel engines with electric buses is due also to the legislation promoted by the EU, namely to the Regulations 443/23 from April 2009 regarding the reduction of the emissions produced by motor vehicles, that sets limits for the CO_2 emissions - 130 (g CO_2/km) by 2015 and 95 (g CO_2/km) by 2020, as opposed to 150 (g CO_2/km) currently [4].

The electric buses can be divided in two categories: non-autonomous (connected to an electric power source during the functioning – trolley-buses) and autonomous, that uses the stored electric energy for powering the drive system consisting of one or more electric machines. Due to the strong development of the electric power storing systems (batteries or capacitors), this bus category has been the center of attention of the motor vehicle and bus manufacturers in the last years.

The autonomy of these buses is limited by the amount/volume/mass of the onboard batteries or capacitors [5].

A fast charging can be carried out at the end of the lines of these buses (or in stations that are located conveniently); when in intervals of 5-10 (min) a high amount of energy is introduced into the batteries in order to compensate the energy lost on the route. Thus the autonomy of the bus is extended; it can operate all day long, as the batteries are brought to the optimum charging level during the night by means of a conventional charging, directly from the tri-phase network [6].

By charging the batteries to full capacity while the buses are parked during the night, in the station or stations at the end of the route (depending on the line considered), the bus has autonomy of 50-150 (km).

In order to avoid the situation of being left without electric energy the bus will be charged for approximately 5-10 (min) at each drive.

Thus, the bus travels the route with the batteries charged almost to maximum capacity, reducing the risk of being left without energy when stuck in traffic for a longer period due to unforeseen situations.

II. Material And Methods

The main functional elements of the bus are: the traction system (the electric machine plus the operation and control elements), the batteries, and the charging equipment either from continuous current (DC-DC converter) or from alternating current (connection elements to the tri-phase network and rectifier for the AC-DC conversion).

While the bus is in motion, the energy flow has the following route: batteries, operation and control elements and the electric machine that converts the electric energy into mechanical energy with an output of over 90%. The obtained mechanical energy is transmitted to the driving wheels with the help of the mechanical transmission elements.

The Electric bus model in AVL Cruise (Fig. 1) includes the following elements: Vehicle (1), Final Drive (2,3), Vehicle Wheels (4-11), Disk Brake (12-15), Electric Machine (16,17), Differential (18,19), Cockpit (20), ASC Control (21), Electrical System (22), Battery (23), eDrive Control System (24), eBrake & mBrake Unit (25), Monitor (26) and Constants (27).

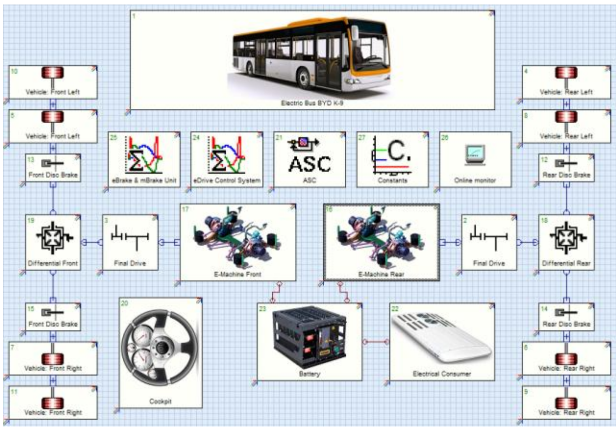

Fig. 1.Electric bus simulation model

The electric system includes an Electric Machine, a Battery, a Control Systems consisting of eDrive Control Unit that will order the transition from e-driving to e-braking and an eBrake & mBrake Control Unit that will order the converting break torque into pressure for all brakes.

Different combinations of the powertrain components can be varied easily and their effect on the consumption in different driving cycles evaluated. The model consists of vehicle, driveline mechanics and e-component models. The required level of model complexity depends on the optimization targets. For energy efficiency optimization, the energy flow simulation from battery to different subsystems and components is essential [7].

The Battery element is a chain of five cells to support the required voltage of the Electric Machine. The Electric Machine component can be used either as an electric motor or as an electric generator. It is possible to charge the Battery while braking or decelerating. The torque coupler is a pair of single ratio gears [8, 9].

For all three models the Central Controller System receives the real-time signals from the driver, which in the simulation model is the Cockpit element and from other individual element, then commands the operation of each element according to the preset control logic [10]. The Cockpit represents the links to the driver and the vehicle. The cockpit serves to define what data and information are available to the driver and what possibilities to influence the vehicle it has.

The Electrical System represents electrical consumers as ohmic resistors in the on-board network. The user defines the number of electrical resistors. The resistance value can be given as a function of any input valve. It is possible to switch each electrical consumer on or off when another input value is exceeded.

The electricity consumption is strongly influenced by a number of factors: the total mass, consumption by auxiliary systems causing a significant increase of the amount of energy consumed from the batteries, part of these factors not being influenced by the distance. At the same time, the route configuration could influence the electricity consumption; it increases under acceleration or when climbing upgrades and decreases when descending downgrades or under deceleration, thus reaching negative values (energy is transferred from the traction electric machine towards the battery).

The Monitor allows for up to ten input channels of the monitor to be connected to the output channels of the calculation of the model runs. The Constant element allows the user to define up to 99 constant values, which can be used by other components through the Data Bus Connections. The values can be of type integer, double or string [11].

The model with the co-simulation interface developed in Cruise will be saved in the working folder TruckMaker/Cruise, where it will be loaded and launched as project work in the application TruckMaker. It will choose the Powertrain folder in the Vehicle Data Set from TruckMaker and in the pull-down menu, choose further AVL Cruise (Fig. 2).

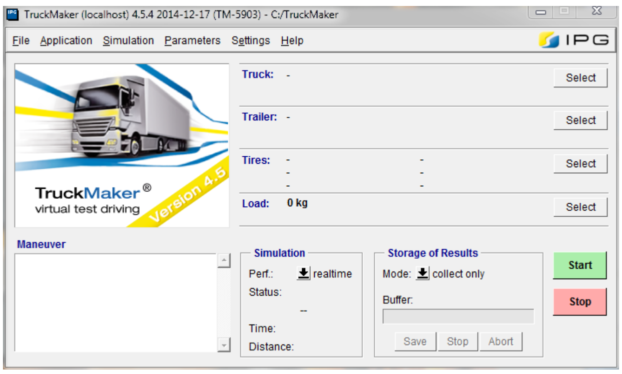

Fig. 2.TruckMaker – Cruise Interface

To evaluate the characteristics of the electric bus and compare it with the IC motored bus used in urban transport (Diesel Euro 3 IC engine) a typical urban drive cycle UDC was run (Fig. 3) which is defined in the Annex III, Appendix I by the Directive 98/69/EC [12]. The total distance of this urban cycle is 8.39 (km), maximum acceleration is 3.66 (m/s^2), the average velocity is 16.87 (km/h) and the total time is 812 (sec) where the bus is stopped in 12 points for 240 (sec), and the engine is at idle speed.

The lightweight bodied bus had an energy consumption of 1.20 (kWh/km) on the cycle; 10 (kWh) in total for UDC cycle.

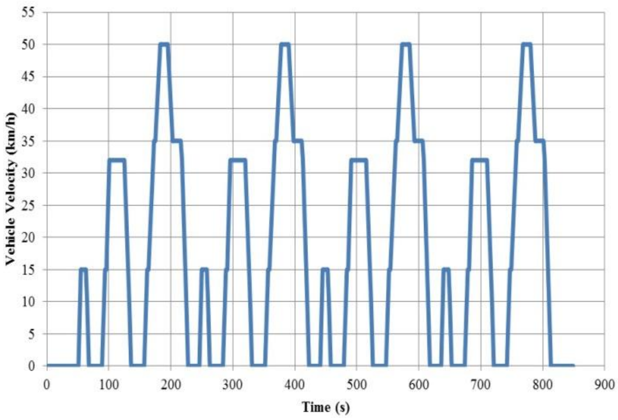

Fig. 3.Urban Drive Cycle (UDC)

The AVL Cruise software offers a comprehensive tool for post-simulation processing of information that emerges during the simulation. The application provides information concerning the accumulated energy consumption, taking into account the charging areas where energy is produced, giving clear and valid information for the entire energy footprint of electric bus model.

To run the simulation, first the model must be connected with Cruise, (connection with the desired model must be checked), and then the road must be loaded, with the desired maneuvers (Fig. 4).

Fig. 4.Run simulation

The first externality type can be quantified starting from the carbon dioxide emissions calculus reported to the fuel (diesel) quantity consumed by an IC motored bus for 100 (km) drive. According to the transaction price of the greenhouse effect gas emissions certificates, the price of a greenhouse effect gas emissions certificate is 12 (€) and a certificate represents the equivalent of one ton of CO_2 emitted into the air [13]. In this way, by replacing the IC motored buses a substantial quantity of emissions is eliminated which otherwise would be emitted into the air (Table I).

TABLE I
COMPARATIVE TABLE SCENARIOS

Parameters	IC motored bus (EURO5)	Electric bus	U.M.
Pollutant emissions CO	1.50	0 Local	(g/kWh)
Pollutant emissions NO_x	2.00	0 Local	(g/kWh)
Pollutant emissions HC	0.46	0 Local	(g/kWh)
Pollutant emissions PM	0.02	0 Local	(g/kWh)
Pollutant emissions CO_2	834	0 Local	(g/km)
Pollutant emissions CO_2	50	0 Local	(to/year)
Energetic efficiency	<40	>90	(%)
Noise level	85-90	55-60	(dBA)

The purchase price of the electric bus type is up to 500,000 (€). The service life (depreciation time) of the electric bus model is 12 (years), and for the battery system in electric buses according to the cycle lifetime estimate, respectively the service life (depreciation time) for the charging equipment was taken as 10 (years) [14].

In Table II, emission costs according to Directive 2009/33/EC that regulated the emissions accounted for CO_2, NO_x, NMHC and PM are presents [15].

TABLE II
COST FOR EMISSIONS IN ROAD TRANSPORT (2009/33/EC)

Parameters	*Value*	*U.M.*
Cost for CO_2 pollutant emissions	0.0400	(€/kg)
Cost for NO_x pollutant emissions	0.0044	(€/g)
Cost for NMHC pollutant emissions	0.0010	(€/g)
Cost for PM pollutant emissions	0.0870	(€/g)

The major cost of the electric bus is its battery replacement, depending on the life of the battery and the cost of replacement. A key factor in the lifespan of a battery is the number of cycles of discharge and charge that the battery can withstand before it loses a certain percentage of nameplate capacity.

The maximum cycle is estimated based on the depth of discharge in each cycle and the percentage capacity lost. The battery is estimated to last approximately 2,000 cycles given 100% depth of discharge and 90% of its original capacity, and more than 10,000 cycles (or 10 years lifetime) on a given 100% depth of discharge and 80% of original capacity. Currently, the price of batteries has dropped significantly to 500 (€/kWh) [16].

III. RESULTS

The result for electrical power and electric motor torque is shown in Fig. 5 and 6. Driving resistances consisting of rolling resistance and air drag correspond with 30% of the total usage (Fig. 7).

The losses in inverter, electric motor and driveline were 20%, of total (Fig. 8). This loss is relatively high in bus driving cycle as the energy flow is fluctuating back and forth all the time in continuous acceleration and braking.

The energy flows in and out of the battery were 15 (kWh) for discharge and the 5 (kWh) for recharging (Fig. 9). This behavior also has an effect on battery losses during the driving cycle 5%, which was calculated using constant 90% charge/discharge efficiency for the battery (Fig. 10).

The actual efficiency measurements will be performed later using battery tester and the actual battery load cycle [17].

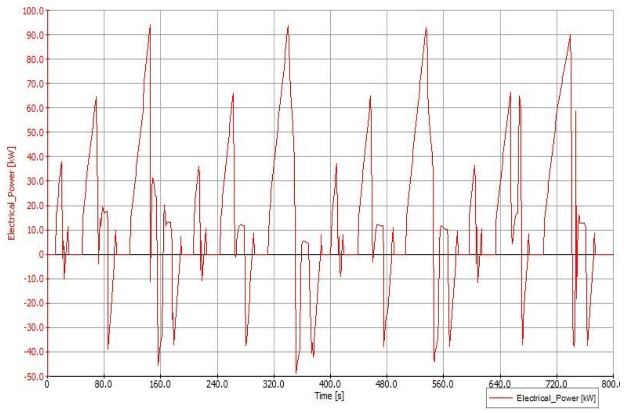

Fig. 5.Electrical Power

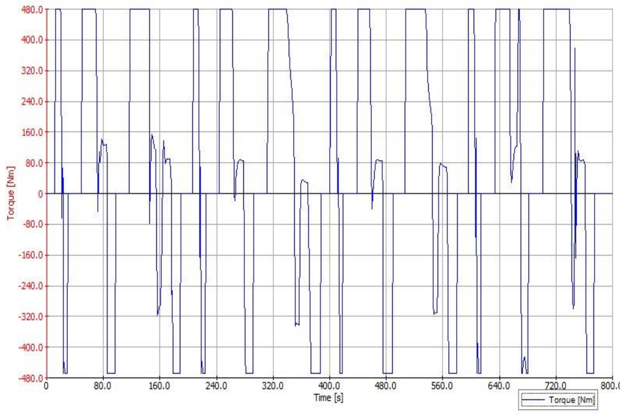

Fig. 6.Electric Motor Torque

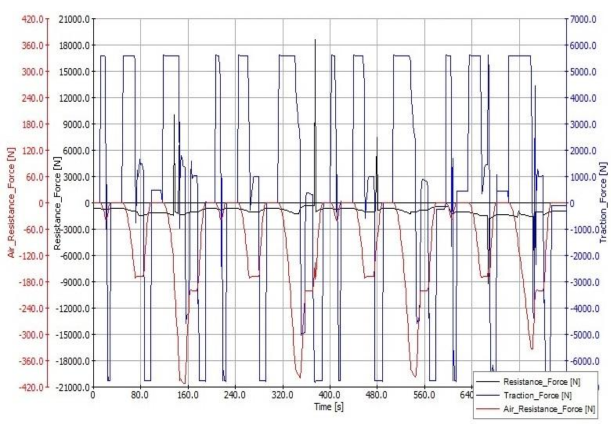

Fig. 7.Driving resistances

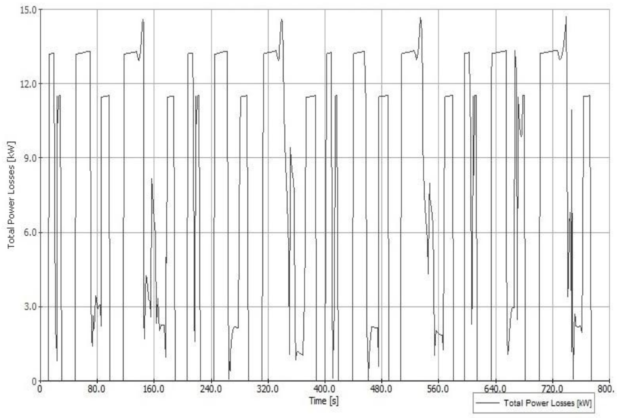

Fig. 8.Total power losses

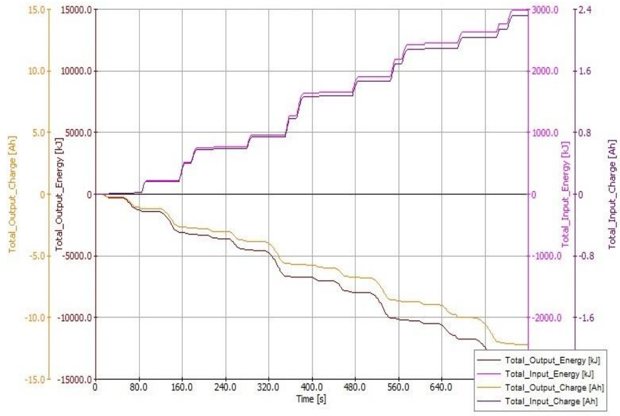

Fig. 9.Battery energies flow

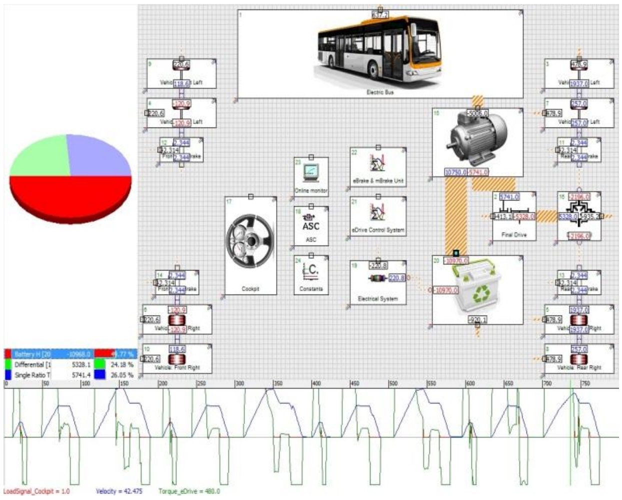

Fig. 10.Battery efficiency

Distributions of energy consumption for electric bus model are shown in the cycle diagram (Fig. 11). The energy consumption in an electric city bus can be studied using a simulation model of the vehicle [17].

The Voltage and Current of the battery in the drive cycle are shown in Fig. 12 and Fig. 13. The State Of Charge SOC of the battery during the drive cycle, are presents in Fig. 14, Electrical Consumption in Fig. 15, Electrical Resistance in Fig. 16 and Efficiency in Fig. 17.

The SOC has a near balance value during the drive cycle. Since the control strategy for braking recovery is not faultless, the generator torque is more than the motor torque and the SOC has a slight rise [8].

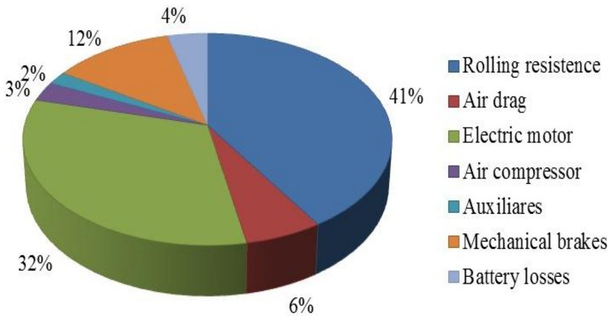

Fig. 11.Distributions of energy consumption

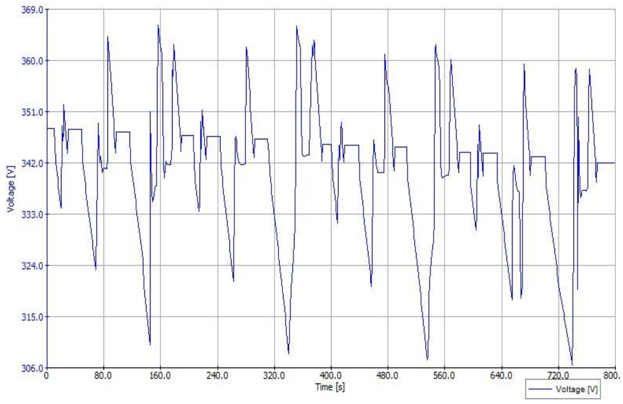

Fig. 12.The Voltage of the battery

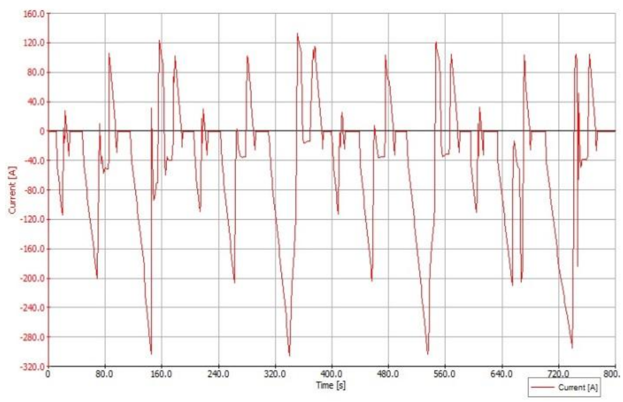

Fig. 13.The Current of the battery

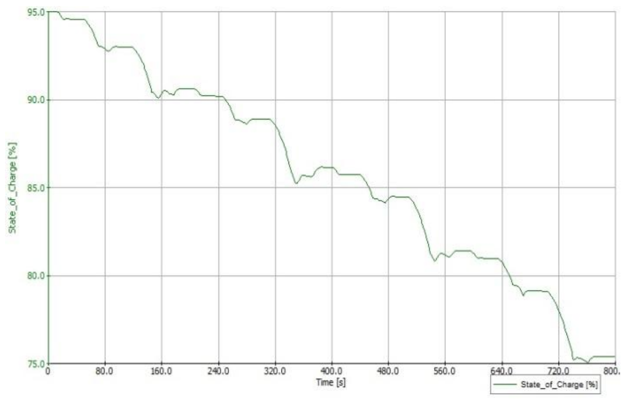

Fig. 14.The State Of Charge SOC of the battery

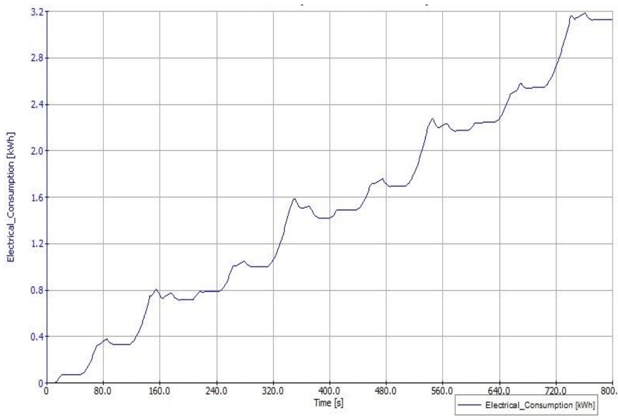

Fig. 15.Electrical Consumption

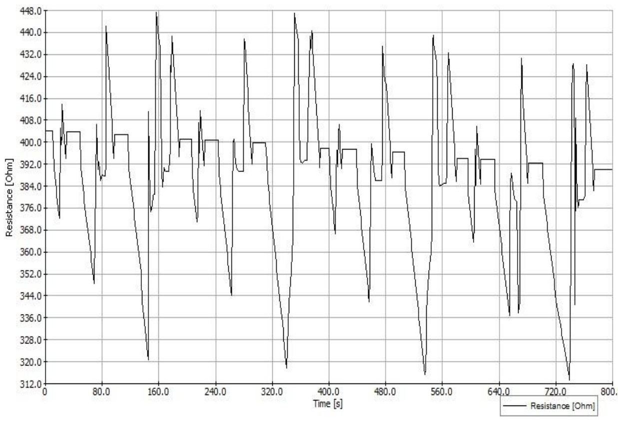

Fig. 16.Electrical Resistance

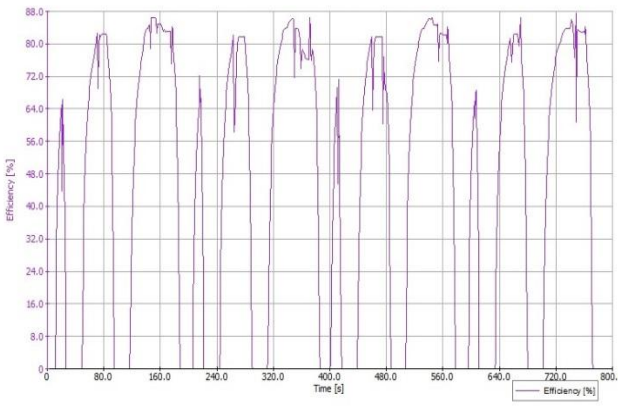

Fig. 17.Efficiency

IV. CONCLUSION

Fully electric city buses have the potential to reduce local emissions the carbon footprint, and noise in historical city center and not only.

An important trend for the future of electric vehicles is the establish the energy efficient strategies that will allow a longer range with less wasted energy by using the most efficient energy recovery systems and planning the urban city lines for the electric city bus taking into consideration a fast charging strategy for each 120 (km)-140 (km) range.

The advantages of the electric buses are:

1) Zero pollution (locally produced emissions);

2) Superior energy conversion efficiency of the electric *machines (>90%) as compared to that of the internal combustion engines (~30%);*

3) Electric machines' ability to operate as generators during the braking periods, the generated energy being stored in batteries, which increases the total efficiency of the system;

4) Electric machines can be placed in the wheels of the bus, in the remaining space the batteries could be placed;

5) Additional batteries can be placed on top of the bus or under the floor, depending on the choice of the manufacturer and/or user, which means more room for the ridership can be gained (for the higher autonomy);

6) Electric energy supply of the batteries generally takes place during the night, as a long-term charging is needed 4–6 (hours), at low value currents, which generally occurs by the direct coupling to the public tri-phase network 400 (V).

As this generally happens during the night, when the buses are parked at the ends of the lines/in the garage, no special equipment are needed in the charging stations, the only problem being represented by the available electric power.

The disadvantages of the electric buses are:

1) Autonomy of these buses is limited by the amount/volume/mass of the on board batteries or capacitors. A large amount of batteries is used for this type of buses in order to ensure an autonomy necessary to function without intermediate charging during the day, which is a considerable disadvantage, as the total mass of the bus is noticeably larger, which has a negative effect on the total energy consumption;

2) Electric buses cannot be used during the charging period, which means that more buses are necessary in order to serve the same number of passengers;

3) *Volume of batteries is significantly higher than in any other type of electric and/or hybrid bus type, which means that their replacement and disposal costs are higher.*

The question remaining to be answered in regard to electrical driven buses is the amount of energy that must be stored for a reasonable range. The main solution for energy storage is the batteries, and the super capacitors. It is obvious that the range of an electrical bus it is only 25-30% from the range of a classical city bus, but as proved it is not needed to be more.

An important trend for the future of electric vehicles is the use of fuel cells that allow direct conversion of a high-energy medium (gas of fluid) to electricity. In the future, the fuel cell vehicle may compete with conventional ICE vehicles [17].

Acknowledgment

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