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Implementing a Hybrid Series Bus with Gas Turbine Device - A Preliminary Study

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Abstract— *This paper presents the implementation of an hybrid series Bus with a gas turbine, as thermal engine. The hybridization methodology for transforming city buses, substituting the original gasoline/diesel engine with a micro gas turbine device (intended as range extender), into a series hybrid vehicle has investigated and its feasibility analyzed. The study was conducted by the university of Rome “Sapienza” in collaboration with several enterprises. The idea is to design a hybrid power train that can be installed in a typical city bus, which means that all systems and components will be influenced by the limited space available. In this paper the details of the mechanical and electrical realization of the power train will be discussed. The hybrid system also includes consideration on the battery pack and the vehicle management logic. The proposed solution obtains a reduction in fuel consumption higher than 20%, in comparison with normal commercial fleet.*

Keywords— Gas Turbine, Hybrid Bus implementation, Hybrid propulsion, Range Extender, System transportation.

I. INTRODUCTION

The first trial of electric hybrid buses power trains with a micro gas-turbine was developed by private company in 2000’s. Three buses were used, with this engine configuration, travelling about 200,000 miles without any problems in urban service [1]. With the use of gas turbine, as a substitute to conventional internal combustion engine (ICE), a lower harmful emissions into the environment has been achieved. For this reason, some of the major public worldwide transport companies have studied and are adopting hybrid configurations. The research has allowed, in June 2010, the entry into service of a 12 buses fleet of hybrid-electric vehicles in Baltimore, assembled with the Capstone C30 micro-turbine. The operating principle of such units is [2]:

“As for the traditional hybrid engines propulsion is provided by an electric motor, while the gas turbine operates to recharge the batteries when they fall below a certain level. This solution provides several advantages, in a quantifiable reduction of pollutant emissions by about 70%, a reduction in power consumption of 40%, and a reduction of noise emissions compared with a conventional bus”.

Starting from these results as reference, the object of this study will be the implementation of a series bus with a gas turbine (GT) device. The study of fuel consumption and emission is effected through the use of software developed internally, the following step, not presented, will be to compare the results with a commercial shareware code ADVISOR.

II. ADOPTED CONFIGURATION FOR THE HYBRID BUSES SERIES GAS TURBINE TYPE

The buses investigated is characterized by specific technical characteristics, in terms of size and performance, similar to a traditional bus, for the people transport on urban and suburban routes. In this case the reference specifications are those of the MAN Vehicle NL 263 F [3] (produced in 2000 and reported in table 1). The adopted configuration is a hybrid series bus with a gas turbine. The configuration (figure 1) involves a GT group, the battery package, the electric motor and a VMU (vehicle management unit) who decides how much energy should be directed to the battery package to charge it and as for the electric motor, as well as control switching on and off of the gas group according to a logic [4,5].

Table.1: Bus specifications

Bus specifications	
Rolling radius	r = 0.465 m
Shape coefficient	f = 0.90
Actual frontal section	$S_f = 7.025\ m^2$
Drag coeficient	$c_x = 0.6$
Rolling coeffcient	f = 0.018
Vehicle mass	m = 10.390 kg
Equivalent vehicle mass	$M_e = 18.500$ kg
Gravity	$g = 9.81\ m/s^2$
Air density	□ = 1.180 kg/m^3

However the system is equipped with a network plug-in system, in case the GT group cannot fully charge the batteries. To simulate the vehicle performance, it is necessary to know a specific route, for calculating the power required by the system bus traction during the mission. In this case an ETC urban path (figure 3) is considered. The route is characterized by an average speed of 10 km/h. This simulation was used to simulate the bus route in Roma, considering two missions, forward leg and back leg (figure 2). The route features are shown in the table 2. To simulate the bus in urban missions, a combination of 6 consecutive ETC urban cycles (figure below) has been evaluated; the whole cycle lasts 4000 seconds in which covers 24.8 km with average speed of 12.61 km/h.

Table.2: Urban Route specifications

Urban route	
Avarage speed V [km/h]	22.6
Maximum speed [km/h]	50
Kilometer per route [km]	12.4
Route time [s]	2400
Stops	18
Total kilometers [km]	

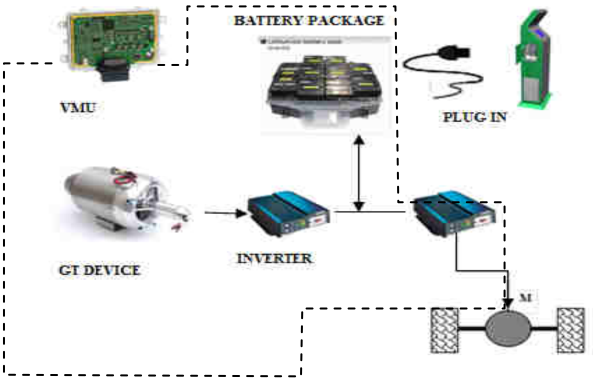


Fig. 1: Basic layout for the Hybrid series bus with GT device

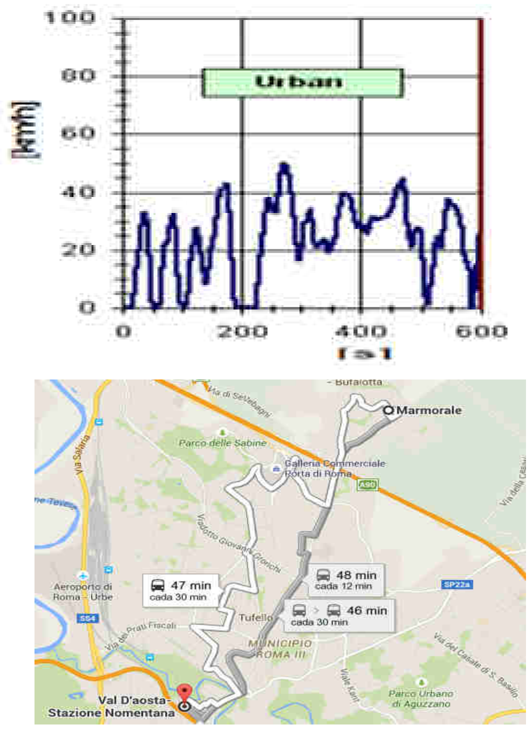


Fig. 2. Time-Speed chart for the considered route and geo-localization

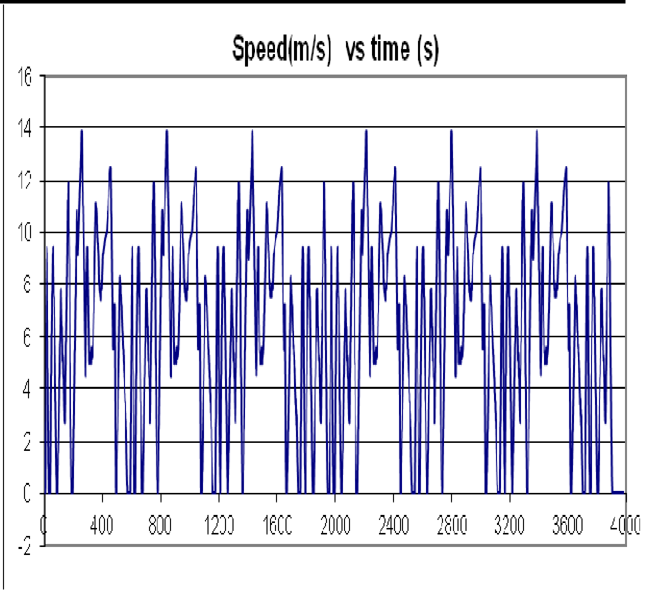


Fig.3: Urban mission: 6 ETC consecutive urban cycles

III. SIMULATIONS CHARACTERISTCS

The simulation basic concept (using a code developed by researchers at the department, called LETHE[@]) is to calculate the power required by the traction system for a given cycle, considering the vehicle dynamics, and always equating to the sum of the power supplied by battery pack with/without GT group. For better flexibility of the traction system, the option of adding and/or predict the presence of another type of battery was considered(i.e. $LiFePO_4$ battery package + ultra capacitors), and the replacement of the GT group with two minor groups power (figure 6) was also considered. The possible accumulator, at the moment, is connected to a motor/generator; responsible for recovering braking energy or a peak power generated by the GT group. The simulation will also consider the degree of hybridization (HD) [6]. This index is defined as the ratio of the GT power installed and the total power installed:

$$HD = \frac{P_{GT}}{P_{GT}+P_{BP}} \quad (1)$$

Ideal for a hybrid vehicle is to get a HD equal to 50%, if not lower. In the simulation, to reduce the fuel consumption of GT group, a regenerated device has been adopted. In the theoretical calculations, the introduction of the regenerator (example Capstone CHV 60 [7]), generates an efficiency equal to 40%. All these considerations will be explained in detail below.

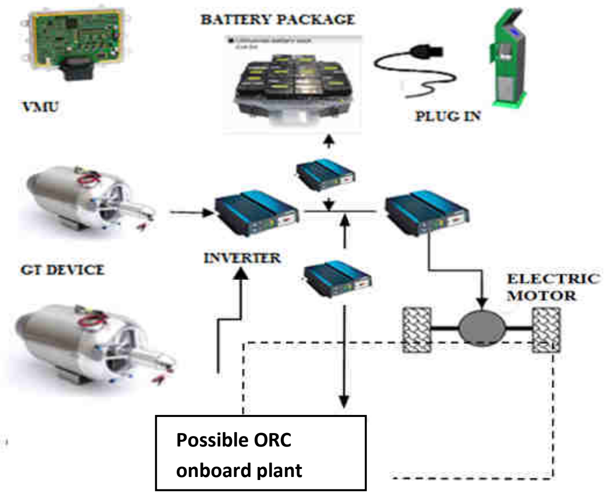


Fig.4:Hybrid Series Bus with two GT groups

3.1 BATTERY PACKAGE

The batteries, in recent years, have had a highly developed that made possible their use in electric vehicles. The most suitable batteries for use in electric traction vehicles must have a high specific energy per unit mass, durability, speed, reliability, compactness, low maintenance and cost. Analyzing the table 3, it can be notice that LiFePO4 batteries has a greater benefit than the others. Several experimental studies performed by the ENEA (Energy & Environment National Agency), suggest the use of the LiFePO4 batteries [8,9], as storage device, in our simulation. It has to remember that these battery package can be recharged in three different modes:

1. by the GT group;
2. by an external charging (plug-in);
3. by the electric motor (braking energy recovering).

Table.3.:Battery package comparison [8]

Chemistry	Nominal Operative Voltage [V] N.O.V	Energy density [Wh/kg]
Lead- Acid	**2**	**30-40**
Ni-Mh	**1.2**	**65-70**
Li-ion	**3.7**	**100-150**
LiPo	**3.7**	**130-200**
$LiFePO_4$	**3.2**	**90-160**
LiTi	**2.3**	**70-100**
Chemistry	Cycle life	Self- discharge rate [%/month]
Lead- Acid	**500-200**	**3-20**
Ni-Mh	**500-800**	**30**
Li-ion	**1000-1200**	**8**
LiPo	**800-1200**	**5**
LiFePO4	**1500-3000**	**< 3**
LiTi	**≥ 4000**	**< 3**

At same time, for the chosen battery package it is possible to supply a series of experimental values. All data is reported in table 4.

Table.4:$LiFePO_4$ Specifications

Module mass m_{mod}	19.1 kg
Module voltage V_{mod}	12.8 V
Cell voltage V_{cel}	3.2 V
Specific Power P_{sp}	201 W/kg
Specific Energy E_{sp}	67 Wh/kg
Battery capacity C	100 Ah
Maximum current C_{max}	450 A

Finally, to determine the correct behavior, the following equations [8] has been implemented in the code.

The battery cell voltage:

$$E = 3.2 + 0.3\ SOC \text{ in charging} \quad (2)$$

$$E = 2.9 + 0.3\ SOC \text{ in discharging} \quad (3)$$

Maximum current for battery package fast charging:

$$I_{max,in} = C_1\ (1 - SOC) \quad (4)$$

(The manufacturer proposing to operate with current equal to the battery capacity (C)).

Battery power.

$$P_{BP,max,in} = V \cdot I_{max,in} \quad (5)$$

with:

$$V = n_{cell} \cdot (3.2 + 0.3\ SOC) \quad (6)$$

so:

$$P_{BP,max,in} = n_{cell} \cdot (3.2 + 0.3\ SOC)\ C_1\ (1 - SOC) \quad (7)$$

It can be notice that in eqtn. (7), battery power is dependent on the State of Charge (SOC) of the battery package. The value of the SOC is limited in the simulation from a minimum of 40% (to avoid deterioration, very restrictive constraint) to a maximum of 80% (for lengthen the battery life).

3.2 GAS TURBINE FUEL CONSUMPTION CALCULATION FOR SIMULATION

A summary of power flows, that lead to the calculation of consumption, is shown in the diagram [10]. Using data interpolation of a gas turbine performance under Off-Design operating range, bounded between 70% and 110% of its rated power, it is possible to get a function that links the performance variation to the power variation:

$$\frac{\eta_{OD}}{\eta_{nom}} = -1{,}333 \cdot \left(\frac{P_{GT1}}{P_{nom}}\right)^4 + 2{,}497 \cdot \left(\frac{P_{GT1}}{P_{nom}}\right)^3 + -1{,}768 \cdot \left(\frac{P_{GT1}}{P_{nom}}\right)^2 + 1{,}646 \cdot \frac{P_{GT1}}{P_{nom}} - 0{,}077 \quad (8)$$

The methane (CH_4) is the adopted fuel, characterized by a lower heating value LHV($_{CH4}$) = 51000 kJ/kg = 14.16 kWh/kg and density δ_{CH4} = 0.585 kg/l. From the study of the thermodynamic cycle and considering a GT efficiency □$_{GT}$ = 0.44, it gets a specific consumption of:

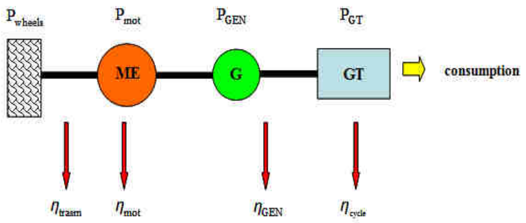


Fig..5:Power flows through the components

$c_{s,nom}$ = 1/□ □$_{cycle}$ · LHV [kg/kWh] (9)

With these data the vehicle fuel consumption for a given mission is so calculated:

• **Specific consumption** (Off-Design) [kg/kWh]

$c_{s,OD} = c_{s,nom}$ · (□$_{nom}$/ $_{hOD}$) (10)

• **Instant c_t consumption** [kg/s]

$c_t = c_{s,OD} \cdot P_{GT}/3600$

where $P_{GT} = P_{GEN}$/□$_{GEN}$ (η_{GEN} = 0.95) (11)

• Total Consumption [kg/mission]

$$c_{tot} = \int_{mission} c_t \quad (12)$$

or in discrete form

$$c_{tot} = \sum_{mission} c_t \quad (13)$$

• **Total Consumption** [kg/km]

$$c_{tot}[kg/km] = \frac{c_{tot}[kg/mission]}{km_{tot}} \quad (14)$$

• **Total Consumption** [km/l]

$$c_{tot}[kg/l] = \frac{1}{c_{tot}[kg/km]} \cdot \delta_{CH_4} \quad (15)$$

• **Total specific consumption** [g/kWh]

$$c_{s,tot}\,[g/kWh] = \frac{c_{tot}[kg/mission]\cdot 1000\cdot 3600}{\int E_{cycle}} \quad (16)$$

with $\int E_{cycle}$ = total energy needed to complete the mission

IV. CONTROL LOGIC

In the feasibility analysis between two different logic [10,11], for simplicity called A and B, only the A logic has been considered. The two logic have the same P_{WHEELS}, vehicle dynamics and same power. The code calculates the P_{WHEELS}, instant by instant, with the formulae:

P_{wheels} = C.ω (17)

since

$R_{tot} = R_{roll} + R_{aer} + R_{in} + R_a$ (18)

$R_{aer} = ½\, c_s\, r\, S\, v^2$ (19)

$R_{in} = M_{eq}\, a$ (20)

$R_a = m \cdot g \cdot tg$□ (21)

□ = v/r (22)

Finally

$C = R_{tot} \cdot r$ (23)

Where R_{roll}, R_{aer}, R_{in} and R_a are the rolling resistance, aerodynamic resistance, inertial resistance and system sliding, resepectively. To calculate the P_{net} the procedure is the following one.

• **P_{net}** that the electric motor must provide during the traction phase is the same for both configuration. In the simulation it has been considered:

P_{net} < 0 (acceleration or constant speed)

$P_{net} = P_{WHEELS}$/□$_{transmission}$ □$_{motor}$ (24)

P_{net} > 0 (deceleration)

$P_{net} = P_{WHEELS}$ □$_{transm}$ □$_{mot}$ □$_{brake}$ (25)

• **SOC** is within 42% to 80% for both logic.

To prevent overloading during recharging phase, it has been established that during any braking phases GT group does not deliver power. This will prevent that the power recovered from the engines can be added with power generated by GT group, generating a total power that could not be absorbed by the storage systems. Also to ensure that the battery discharge does not fall below the designed minimum, it is implemented in code, the history of batteries. If the battery has suffered a total discharge, whatever the power demand of the system (even nothing for stationary vehicle) will be supplied by the GT group, to ensure a level of charge equal to SOC_{max} when batteries will again be used to provide power.

• **Power-Check**

The A logic that controls the gas turbine operative conditions are reported in table 5

Table 5. Turbine Operative conditions in Logic A

Power check	IF	GT_1	GT_2
0	$P_{GEN} < P_{GEN1,min}$	off	off
1	$P_{GEN} < P_{GEN2,min}$	on	off
2	$P_{GEN2,min} \leq P_{GEN} \leq P_{GEN2,max}$	off	on
3	$P_{GEN2,max} < P_{GEN}$	on	on

V. SIMULATION

With the different components and the logic described above, we proceed to calculate the battery package installed power, the GT groups rated power, the fuel consumption and emission for the proposed hybrid series bus, in the two proposed routes. The simulations have been carried out using Lethe[@] code, developed by the research group. In the code the all above parameters are used to study the chosen configuration, and indicate, firstly, the "quasi-optimal" logic to adopt, and then, to supply a preliminary design of the interesting components, as well as the GT group, the battery package, the flywheel, if any, and the electric motor.

5.1 SYSTEM ANALYSIS BY LETHE@ CODE

The simulations, as previously described, consider the needed power and speed to the wheels to complete the given cycle and determines the powers that each system components has to generate and/or absorb to satisfy the power request. This process is repeated according to second. Also it is assumed that, in the Δt interval between two consecutive time-steps, all the variables of interest (required and supplied power, speed, acceleration, braking, SOC level, flywheel energy, etc) remain constant. The management logic provides, once the mission is accomplished, the battery package is recharged by the GT until initial value; this condition was considered in all simulations for evaluation the total fuel consumption. The first step is to set the number of battery modules, namely P_{BP} installed power. Once P_{BP} is set, is also known the range $P_{BP,max,in}$, SOC-dependent, which can absorb the battery being charged. Remember that the GT group power may vary between 70 and 110% of the nominal power. The P_{GEN1} is determined as follows. It requires that the GT power output, when working at 70% of the nominal value, is equal to the minimum value of $P_{BP,max,in}$, which corresponds to the value of SOC_{MAX}. A constraint imposed, in the simulation, is that the GT group must be able to fully charge the battery pack, independently. The P_{GEN2} is established as follows. The sum of P_{GEN1} and P_{GEN2} must be equal to the maximum power required by cycle. The GT powers are then combined together, alternately and iteratively reduced until the minimum fuel consumption (while respecting the constraints of instant satisfaction of power demand and energy balance, i.e. every second). The procedure is repeated by varying the number of battery modules. Numerous solutions have been simulated. Specifically, it reports the results of the simulations with different approaches and different GT sets. The simulation "boundary conditions" are shown in table 6. In the first simulation a 50 kWh battery package (BP) was considered. Then calculations were repeated with 100 and 150 kWh PB.

Table .6.Simulation specifications

Logic	**A**		
	A1	**A2**	**A3**
GT_1	30	60	30
GT_2	0	0	60

The SOC trends for various configurations are shown below. It can see, how, in the first two simulation (A1 and A2) to the first half of the mission (2000 seconds) is carried out in pure electric mode, the remaining 1902 seconds, the turbine is switched on (represented by the black dot in the figures), to recharge the BP. In the case of a 30 kW GT group, the SOC at the end mission is a little bit greater than 0.4, while in the second case is about 0.6. Finally in the last case the SOC at the end of mission is the same as the initial one (0.8). It is important to notice and recall, that the first simulations have been carried out with a 50 kWh battery package. The simulations have been repeated with a 100 kWh and with 150 kWh BP, and the SOC values shown in figures 7 and 8. In the case of 100 kWh, nearly the 75% of the entire mission (about 25 km) is covered in pure electric mode, with different values of SOC due, as in the previous case, the rated power of the GT group installed. In the latter case, almost the entire mission is electric. This latest simulation is very indicative. In fact the best solution (in the case of "*pure electric mission*"), as it is shown below, is the A2 case, with a group from 60 kW, which allows a faster reload of BP.

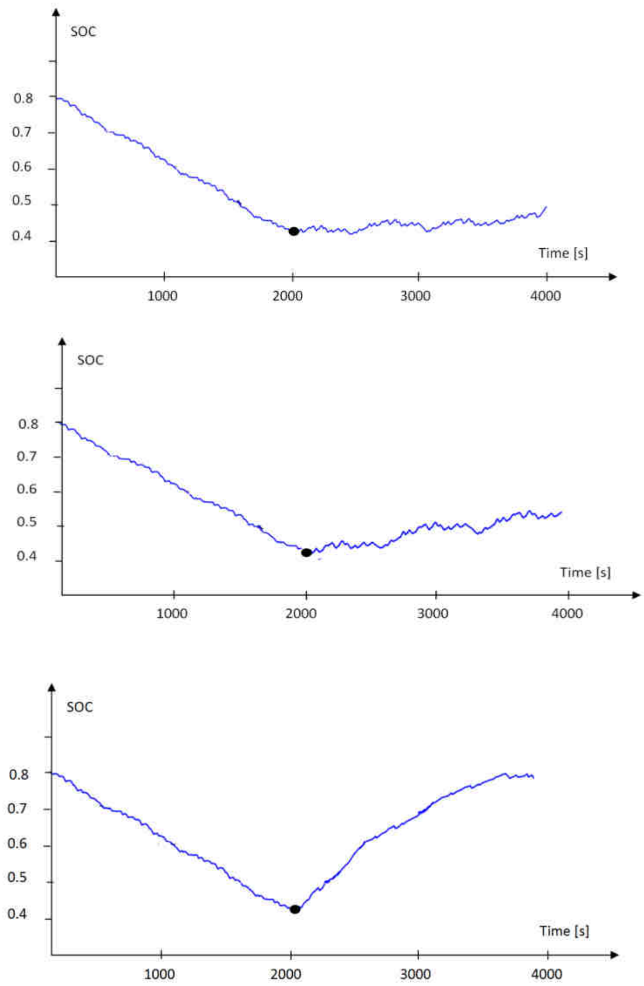


Fig.6: 50 kWh BP SOC trend; a) 30 kW GT; b) 60 kW GT; c) 30+60 kW GTs

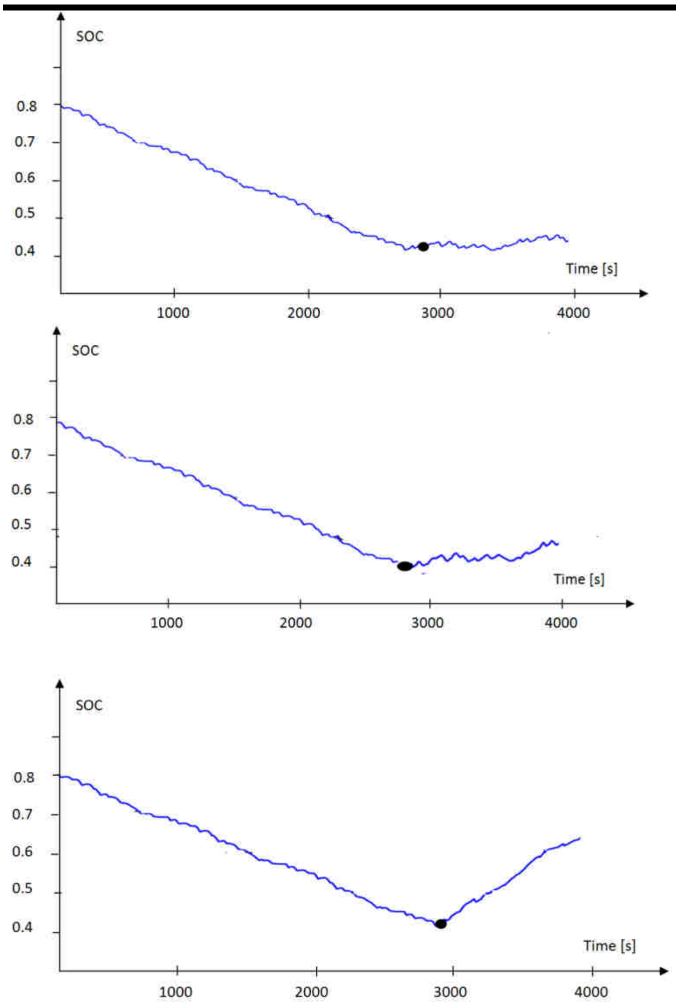
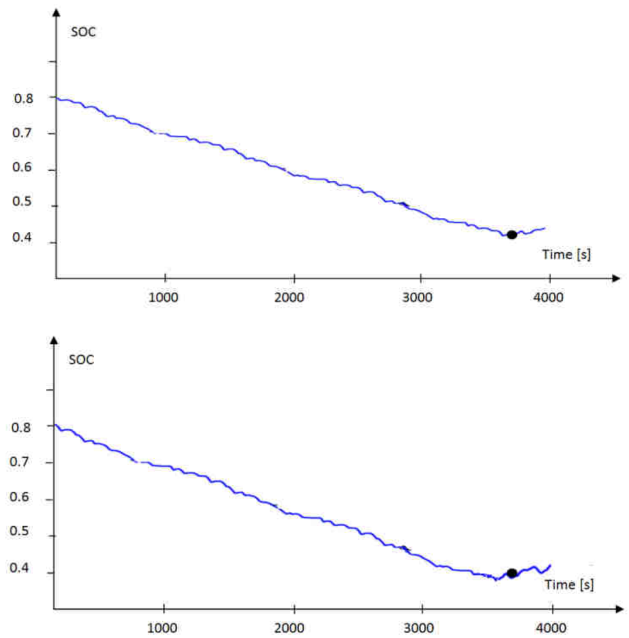


Fig. 7:100 kWh BP SOC trend; a) 30 kW GT; b) 60 kW GT; c) 30+60 kW GTs



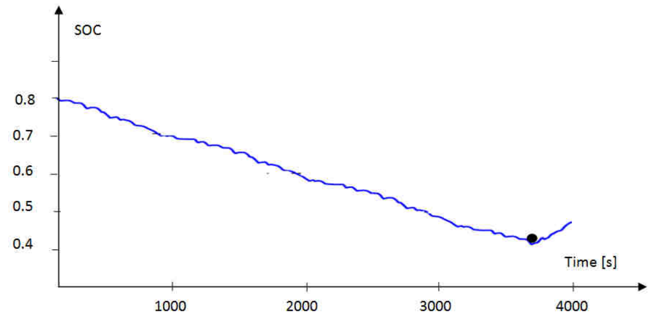


Fig.8: 150 kWh BP SOC trend; a) 30 kW GT; b) 60 kW GT; c) 30+60 kW GTs

It can be notice, preliminarily, the fuel consumption values (for the first sets of simulations) are very close to the actual commercial bus fleet (see table 8 for fuel consumption comparison). Also in this case, the simulations confirms the validity of the control logics adopted, as well as the choosing criteria of the traction system components. In fact, in the first simulations (the “worst” from every point of view) a 47.7 l/100 km is obtained. It is comparable with the actual commercial fleet [12], but it is important to consider that the fuel used is methane (CH_4) or liquid gas (LGP). The environmental impact is lower than the diesel powered bus fleet. In the other simulations the fuel consumption is lower with undoubted benefits on the city environment. Another remark. The SOC curves, as well as all curves that the code supplies, are obtained considering a BRL = 1C. The letter “C” means the BRL does not exceed 1C here: possible higher values can be obtained (actual common practice accepts a 2C in recharging and a 4-6C in discharging operation), but it is limited to operate in safety conditions. Change this value the recharging operation is shorten and the a “transportation service continuity” can be assure.

Table.8: Commercial bus fleet (diesel powered) fuel consumption

Type	**Fuel consumption [l/100 km]**
Iveco FCA 480 12.21	52.1
Iveco 491g 12.27	54.7
Iveco FCA 480 12 22	56.3
Breda Menarini M220/E	46
MAN NL 263F	48
Hybrid Bus	47.7 (LGP or CH_4)

VI. BUS HYBRIDIZATION OVERVIEW

The procedure proposed is not so "complicated". In fact, the hybridization of a commercial vehicle, currently circulated in urban areas, can be achieved without excessive effort. In our case, it results in eliminating the

ICE engine and all its transmission assembling, and replace it with a two 150 kW electric wheel motor (EWM) and 60 kW GT set. Note the dimensions, it can be notice how the whole system does not affect the bus structure. The lower compartment can be used to insert the battery package, leaving the bus barycentre in the same place of actual commercial bus. GT can be placed in the engine compartment with all auxiliaries All these considerations are represented on figure 9. Once the components have been "located", it is passed to the calculation of weights. It can be notice how that the configuration is only "simulated", in that a prototype has not been yet realized.

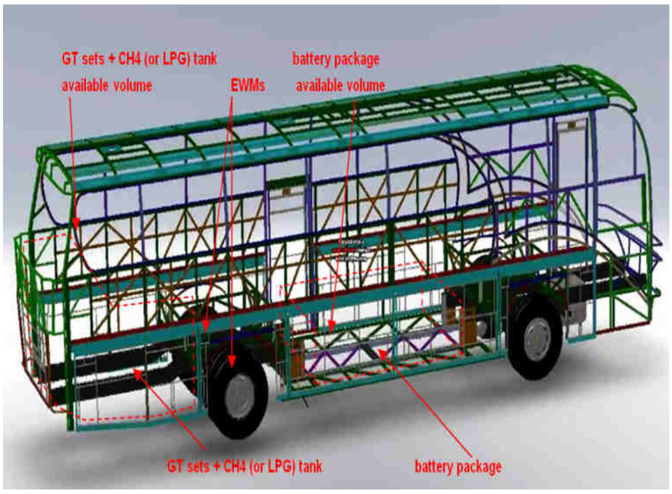


Fig.9: Possible layout for the Hybrid Bus

The distribution of the components has been studied on the frame of referenced bus. The frame was rebuilt, once its structure and dimensions were known, using the dedicated software program, and it was used to check the size of the components for our chosen configuration. When positioning the rotating parts, the respective gyroscopic movements were considered, although they generally appear to be less important than the one generated by the wheels. However, it is necessary to consider the fact that a mass rotating around a vertical axis can link rolling and pitching, while a rotating mass around a longitudinal axis can couple the pitch to the yaw. For this reason, all the rotating parts are placed with a rotation axis that is parallel to the wheel axis, whose gyroscopic effect can be contrasted by appropriate balancing of suspensions. Finally, although safety was not an issue involved in this work, the battery pack was placed on the main frame, under the middle seats, in order to respect "crash protection" conditions and to be easily accessed for maintenance or battery-package replacement. The advantages to this configuration are multiple. First, the utilization of wheel engines eliminates the transmission (heavy and bulky) and increases the capacity of the battery package. On the other hand, both motors needed a lubricating/cooling circuit, resulting in an increasing of system complexity and costs. The cost analysis has not been performed, but it is the last step for the realization of an operational prototype and for searching possible investors.

VII. CONCLUSIONS

The results analysis shows how the proposed implementation is feasible. In fact in all simulations of the considered configurations, the specific consumption (one of the project target and constraint) is always lower than the current commercially available buses. A 47,7 l/km of fuel consumption is obtained in the more restrictive and penalized configuration.

In detail, the proposed solution has many positive aspects. the first is the reduced fuel consumption and a lower environmental impact. The use of a GT and a gaseous fuel, reduces emissions, and in the specific case the emissions of PM, that seriously afflict the city environment nowadays.

Another positive aspect is the "non-destructive" transformation of the vehicle. In this context it could use all those buses that are discarded because out of date, non respecting EU standards or more. This way you the disposal costs will reduce, implementing a real policy of recycling.

At this stage, it appears that a confront simulations with other codes used for hybrid vehicles. This will inevitably lead to improvements and to the choice of the bus configuration, that satisfies all requirements. A detailed weight distribution is required, but this can be performed only once the prototype is realized.

It is therefore essential an economic analysis (i.e. capital costs, pay-back time, etc) for the realization and assembling of the prototype. Only through this study it can see if an hybrid bus is feasible and, at the same time, competitive. The economic analysis will also be used to get a detailed "description" of future possible investments.

In fact, the analysis, confirm as the first obvious advantage is the lowest environmental impact resulting from the use of LPG or methane (CH_4) as fuel. In times of circulation limitation, due to high values of PM (due to diesel vehicles), a means of circulating electric/gas would drastically reduce such emissions. A second positive aspect that would bring such a system is significant cost savings in the year. It can be notice that, at a cost of 1.25 € per liter of diesel, for a distance of approximately 1346 km per day, staring at an average consumption of 50 l/100 km, would be necessary 673 liters of diesel, at a cost of about € 840 per day per bus. In the year that cost would become 302,800 €. If be used hybrid buses, the cost of fuel for the GT group would (cost € 0.97 €/l or LPG methane cost 0.5/l) amounts to 113,870 € and 220,900 €

respectively. It is essential to note that this would be the annual savings per bus. The percentage gain in economic terms is of 28% in the worst case. In terms of fuel consumption, at worst (logic A1) saving is of 16%.

NOMENCLATURE

BP	battery package
BRL	battery recharge levelC current [A], capacity (section 2), Torque [Nm] (section 3)
c_s	drag coefficient
E	energy
ETC	European test cycles
EWM	electric wheel motor
f	shape coefficient
GEN	generator
GT	gas turbine
HD	hybridization degree
LPG	liquid gas petroleum
M, m	mass [kg]
P	power [W]
r	radius [m]
SOC	state of charge
R	resistance
V	velocity [m/s] (section 1), voltage [V] (section 2)
VMU	vehicle management unit

Greek symbol

□	density [m^3/kg]
□	radial velocity [s^{-1}]

Subscripts

BP	battery package
GEN	generators
GT	gas turbine
Nom	nominal

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