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Development of a new hybrid bus for urban public transportation ☆

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HIGHLIGHTS

- New plug-in series hybrid electric powertrain developed for revamping old urban buses.
- Assessment of its performance through experimental tests in real world operating conditions.
- Impressive energy and operating costs savings vs conventional buses highlighted.

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ABSTRACT

Nowadays the increasing demand for sustainable mobility has fostered the introduction of innovative propulsion systems also in the public transport sector in order to achieve a significant reduction of pollutant emissions in highly congested urban areas. This paper describes both the design and the optimization of an environmentally friendly hybrid bus (hereafter referred to as "HYBUS") for urban public transportation.

After a preliminary description of the main features of the hybrid architecture, this paper assessed, through numerical simulations, the fuel economy potential of the hybridization in real world driving conditions. The promising results of this first part of the study led to the development of a first prototype.

The first prototype of the bus was built by integrating an innovative hybrid propulsion system featuring a plug-in series architecture into the chassis of an old IVECO 490 TURBOCITY. The bus is 12 m long and capable to host up to 116 passengers in the original layout. The project relied on a modular approach where the powertrain could be easily customized for size and power, depending on the specific application.

The prototype was then extensively tested in the city of Genoa, Italy, an urban context extremely challenging for a hybrid powertrain due to its frequent uphill routes and significant road grades. The outcomes of the test campaign confirmed the simulations forecasts, and fostered additional analysis aimed to optimize the energy management strategy of the hybrid powertrain.

Numerical simulations were then used in order to identify more refined energy management strategies capable of further enhancing the fuel economy potential of the hybrid architecture. Consequently, a novel energy management was developed, and virtually tested, to manage the HYBUS in a more effective way. The results demonstrated the interesting potential of such hybrid architecture.

1. Introduction

In a context of the global economic downturn, the high demand for sustainable transportation and for cost reduction for transit agencies could meet halfway. Indeed, fuel cost represents one of the most significant portions of transit agency budgets (by way of example for the 2012 for the Turin Transit Agency fuel cost was equal to 22% of sales proceeds [1]) and its reduction directly corresponds to a cut of CO_2 emissions. As a consequence, bus hybridization offers an attractive option in this direction and has the potential to significantly reduce operating costs for agencies.

Simulation tests have highlighted the strong capabilities that different hybrid bus concepts can exploit in terms of better fuel economy [2–4] and lower emissions compared to conventional buses equipped with Internal Combustion Engines (ICEs).

Although the best enhancement in terms of fuel consumption is usually reached by means of powertrain architectures with high

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Nomenclature

Definitions and Abbreviations

APU	Auxiliary Power Unit
BMEP	Brake Mean Effective Pressure
BMS	Battery Management System
BSFC	Brake Specific Fuel Consumption
DP	Dynamic programming
EEV	Enhanced environmentally friendly vehicle
EM	Electric Motor
EMS	Energy Management System
EV	Electric Vehicle
GTT	Gruppo Torinese Trasporti
HEV	Hybrid Electric Vehicle
HHV	Hydraulic Hybrid Vehicle
ICE	Internal Combustion Engine
OOL	Optimal Operating Line
PID	Proportional Integral Derivative
SOC	State of Charge
SORT	Standardized On-Road Test Cycles
VMU	Vehicle Management Unit

flexibility like Hybrid Electric Vehicles (HEVs), to date HEVs had not been widely adopted due to their high costs related mainly to the battery pack. Therefore, sometimes low cost hybridization solutions such as for instance Hybrid Hydraulic Vehicles (HHVs), seem to be more attractive even if they exhibit lower efficiency compared to equivalent electrified powertrains [5].

However, the amount of case-studies focused on hybrid buses and their experimental testing which is available in literature is still limited, although in the last few years it is possible to cite several examples of agencies that are currently employing experimental HEV buses in their fleets [6–11] to assess their real performance. Moreover, fuel economy can vary according to a huge number of factors, including number of stops per unit distance, road grade, surrounding traffic volume and conditions, environmental conditions, driving style, type of hybrid technology, roadway type, and passenger load [12–14].

For these reasons the real fuel economy gain which can be gathered during in-use vehicle operation sometimes leads to results which are very different from those expected.

Finally, it has to be mentioned that an additional barrier to the wider diffusion of hybrid electric buses is represented by their significantly higher purchase cost (approximately 50–70% higher) [15] in comparison with conventional diesel urban buses.

The HYbrid BUS (HYBUS) project, carried out in cooperation between Politecnico di Torino and Pininfarina, Italy, aims therefore to address the abovementioned issues, trying to reduce both the fuel consumption and the purchase cost of a new, environmentally friendly urban bus, which has been conceived through the study of a modular hybrid propulsion system, allowing the conversion of old vehicles currently equipped with Euro 0–1–2 diesel engines into buses with serial hybrid power packs.

The core idea of the project is to exploit the older buses present in the agencies' fleets, which can be still fully functional, but with pollutant emission rates too high to comply with current legal limitations: in the HYBUS the original diesel powertrain of an old IVECO 490 TURBOCITY (12 mt. long, 116 passengers urban bus) was removed and replaced by a new generation plug-in series hybrid powertrain. Moreover, thanks to the modularity of the proposed hybrid architecture, the powertrain could be adapted to different types of urban busses.

The cost saving is estimated to be about 50% compared to a new conventional diesel bus (for which a price estimate between 220–290 k€ can be made [16,17]) and about 60% compared to a new hybrid bus (for which a price estimate of about 350 k€ can be made [18,19]).

Such an approach could obviously not be considered the ultimate solution towards the green urban mobility: however, although a retrofitted bus, will not last as long as a new hybrid bus, with its upfront savings compared to a factory-new solution, it could pave the way to a fast upgrade of the fleets, allowing a gradual and affordable introduction of new advanced HEVs.

This article describes in the next Section 2 the steps that led to the HYBUS prototype production, from the concept idea to the design and manufacturing, as well as the first testing phases under real world operating conditions in the city of Genoa, Italy. Afterwards, in Section 3 the set-up, validation and exploitation of a numerical model of the HYBUS is described, in order to assess the potential of the selected hybrid powertrain in terms of fuel economy and to provide a virtual test rig for the development of more advanced energy management strategies, which are discussed in the last Section 4.

2. HYBUS development and experimental assessment

2.1. Powertrain requirement evaluation

The revamping of a bus, with the goal to realize a completely new powertrain, requires the knowledge of the typical mission profile and of the main features of the vehicle.

For these reasons the first step of the project was the identification of a bus potentially suitable for the task. After a brief research among the Turin transit agency's fleet [20], the IVECO TURBOCITY UR-GREEN – EURO 1 was selected since it represented the largest fraction of the older buses in the agency's fleet, and by upgrading this model alone, more than 10% of overall vehicles of the Turin transit agency [21] could reduce their environmental impact in the city center.

The main features of the vehicle are summarized in Table 1.

As far as the driving pattern is concerned, the Standardized On-Road Test Cycles (SORT) 1 (Heavy Urban) and SORT 2 (Easy Urban) cycles [22] were initially used to obtain, through a simple kinematic model [23], a first estimate of the vehicle road load during typical operating conditions.

Although traction power peaks during the abovementioned test cycles can be larger than 150 and 200 kW, the average traction power levels do not exceed 6 and 10 kW, respectively on SORT1 and SORT2 [2].

Benchmarking analysis on other buses of the same category led to set the additional quantitative targets which are reported in Table 2.

Table 1
TURBOCITY UR-GREEN data.

Dimensions (mm)	12,000 × 2500 × 3130 (L × W × H)
Wheelbase (mm)	6150
Wheel track (mm)	Front 2086 Rear 1836
Curb weight (kg)	11,180
Max. total weight (kg)	19,000
Frontal area (m^2)	7.5
Drag coefficient (–)	0.8
Tire rolling resistance (N)	$0.006 + 0.23 \times 10^{-6} \times V^2$ (with V(km/h))