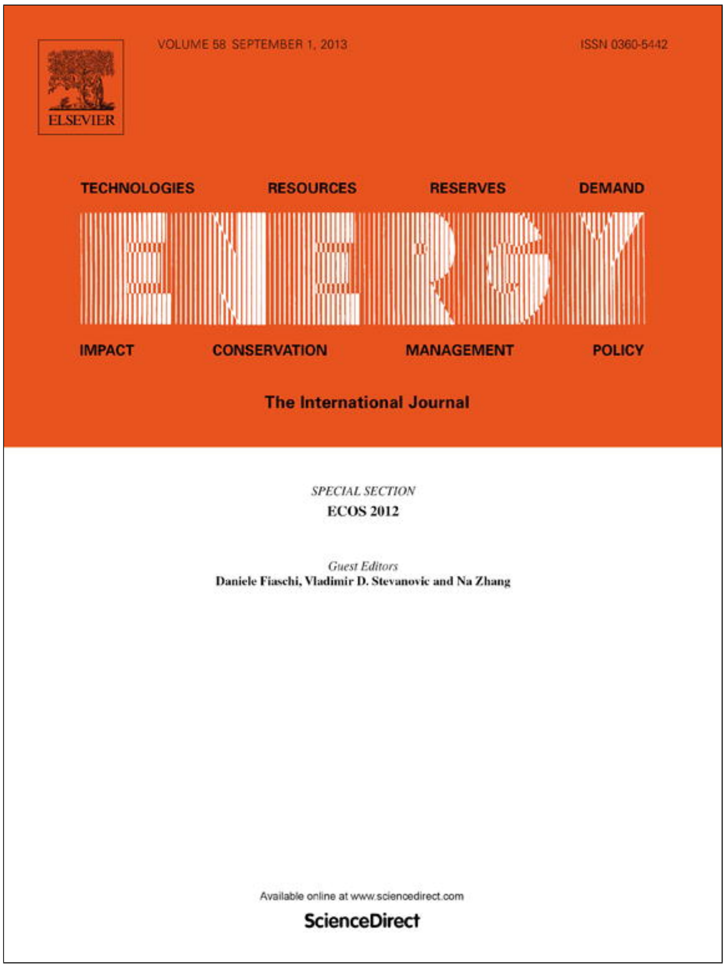
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The *LETHE*© (Low Emissions Turbo-Hybrid Engine) city car of the University of Roma 1: Final proposed configuration

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ABSTRACT

A longstanding interest of the Authors' research group at University of Roma Sapienza (UDR1) is the design, development and fielding of a road prototype of a new concept of Hybrid Series vehicle, endowed with a small Gas Turbine set as a thermal engine. This solution offers several advantages with respect to traditional internal combustion engines and even to the existing generation of Hybrid propulsive systems: a reduced engine weight and size, lower emissions, substantially extended range, ease of maintenance, and more efficient braking energy recovery. In the LETHE© (**L**ow **E**missions **T**urbo-**H**ybrid **E**ngine) the GT (gas turbine set) does not directly provide traction, but serves solely as a battery pack recharger. The vehicle is, in all respects, equivalent to a purely electric vehicle, except for the presence of an on-board recharger. Much care was placed in the design phase in the quest for an "optimal" design: first of all, an original method for identifying the most convenient degree of hybridization (ratio of the installed power of the battery pack to that of the GT) was defined and formalized, so that the resulting power balance between the two units satisfies the main design specifications and guarantees a practically acceptable operational life of the battery package while enabling the vehicle to complete a typical city mission (about 25–50 km) in a purely electric mode and without recharge. This paper presents a review of the previous conceptual and design results and describes in detail a possible road prototype configuration (weights, packaging of all units within the body of the vehicle, logic control unit, GT- and electric motor size and power, battery package characteristics). Some discussion is also devoted to the foreseeable impact of the deployment of a LETHE© fleet on the mid-range scenario of the Italian urban transportation system.

1. Introduction: a brief review of existing hybrid vehicle concepts and of current market opportunities

In the last decade, governmental incentives and the ever stricter emissions regulations have prompted some of the largest world automakers to allocate resources to the study, design, development and production of hybrid vehicles, which offer undisputed advantages in terms of emissions and fuel consumption with respect to traditional internal combustion engines. In fact, true hybrid engines are substantially smaller than conventional i.c.e. (internal combustion engine), because they are designed to cover the vehicle's "average" power demand, which ensures proper traction for about 99% [12] of the actual driving time, and is exceeded only for prolonged mountain drives and instantaneous accelerations. When excess power above this average is needed, the hybrid vehicle relies on the energy stored in its battery pack. Hybrid cars are often equipped with braking energy recovery systems that collect the kinetic energy lost in braking, which would be dissipated into heat otherwise, and use it to recharge the battery. Smaller sizes of the thermal engine and an (almost) constant operational curve lead to lower emissions. Moreover, a hybrid vehicle can shut down completely its i.c.e. engine and run off its electric motor and battery only, at least for a limited operational range: this "mixed operation" increases the net mileage and releases a substantially lower amount of pollutants over the vehicle lifetime. Due to market demand though, current commercial HV (hybrid vehicles) are mostly passenger hybrid cars equipped with a traditional i.c.e. and an electric motor coupled in parallel. The thermal engine is normally oversized with respect to the average power, and the surplus power needed during rapid acceleration phases is supplied by the electric motor: as a consequence, fuel savings are limited, as are global emissions, and the electric range is severely limited.

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2. The LETHE© concept

The series hybrid configuration developed by the authors' research group [5–7], nicknamed LETHE©, is a vehicle in which two natural gas fuelled small turbogas sets are coupled to high speed electrical generators and a lead-acid battery package: the vehicle can operate in electric-only mode if requested, or in hybrid mode, where the gas turbine and the battery package operate together to satisfy the power demand [6]. The traction is fully electric in either operational mode.

In the hybrid vehicle scheme discussed in this paper, the electronic "VMU" (vehicle management unit) controls ignition and on-off switching under a Load Following logic. The VMU decides at each instant time how much of the energy produced by the GT (gas turbine set) reaches the battery package or the electric engine directly. In addition, the electric motor can also act as a dynamic brake, recovering much of the energy that is otherwise dissipated into heat. In order to maximize the recovered energy and to avoid possible battery overloading, an additional dynamic storage unit has been included: a relatively small flywheel capable of storing the excess power from the regenerative braking and of releasing it at a later time according to the instantaneous power demands. The VMU performs its energy-management task on the basis of a certain number of instantaneous mission parameters: the batteries may thus provide or absorb the difference between the energy requirements of the vehicle and the GT energy production. The generator acts as a starter for the GT as well. A continuous GT control can be enforced via fuel flow control and/or employing a variable geometry GT. Since GT power modulation is affected by a substantial efficiency penalty at off-design conditions, the fuel flow control is coupled with a variable-stator turbine and the IGV (inlet guided vanes) blades for the compressor.

As any other system, the GTHV (gas turbine hybrid vehicle) has advantages and drawbacks [8]. The following parameters ought to be considered when selecting/designing such a system:

- The GTHV has a small number of moving parts;
- It is of compact size and can be comfortably mounted in the engine compartment of a sedan or of a smaller city car;
- Both the micro turbines and the electric engine have a very high power-to-weight ratio;
- In the configuration adopted here, the GTHV attains a very high fuel economy;
- The GTHV has a lower emission level, with effective multi-fuel capability;
- There is the possibility of improving the overall vehicle design and to increase the payload thanks to weight and size savings; All components have a high reliability.

On the other hand, the proposed configuration has some drawbacks:

- The battery package has a rather low power-to-weight ratio;
- The SOC (state of charge) trend during any mission must be monitored to avoid overcharge and excessive discharge of the battery pack [2];
- The GT may be subjected to several ignitions during a mission, which negatively affects its MTBF (mean-time-between-failure);
- There is the necessity of monitoring and satisfying the instantaneous vehicle total power demand.

3. The degree of hybridization

The mechanical power in a series HV vehicle is typically supplied by one EM (electric motor), so that, from the traction point of view, the vehicle is in fact an electric one. The choice of the EM is a direct function of the required performance. In the procedure of the HD calculation we identify two solutions: the first one is a "double electric" source, with the battery pack and thermal engine generating all electric power required by the EM (i.e Toyota Prius). In this configuration the vehicle can operate using only the battery pack in a total electric configuration.

The second solution is a "minimal electric" configuration: battery pack and thermal engine simultaneously provide all electric power to the EM (on the other hand the absence of one of these power fluxes compromises the vehicle performance). Specifically, the battery packages does not have the sufficient power required by the traction, and without the i.c.e. the vehicle is not able to perform the mission for which it is designed. The design problem is then that of identifying the electric source that minimize weight, volume and engine cost [6] while providing a sufficient driveability throughout the prescribed mission(s). Once the maximum required traction power is fixed, then the total power source supplied by the i.c.e. and battery package can be calculated from the overall mission energy balance. Thus, the Hybridization Degree (HD) can be calculated as the ratio between the GT power and the total installed power (GT plus battery package).

$$\mathrm{HD} = P_{\mathrm{GT}}/P_{\mathrm{GT+BP}} \tag{1}$$

Our design target is to attain the minimum possible HD that still guarantees a good driveability under all possible conditions. To find the correct HD we have adopted a method based on an energy balance evaluation, step by step, with a time step of 1 s [3,4,6]. The typical performance characteristics of an i.c.e. (wide operational power range and easy connection to the wheels) cannot be applied in our case, where the thermal engine is a GT set which has a very limited operating range and rotates at regimes (usually >25,000 rpm) which make a direct or indirect connection to the impractical. This forces the designer to use the GT set as thermal source and the hybrid series configuration results as a natural choice.

Moreover, while it is obvious that modern i.c.e. have better fuel economy than TG under steady, peak-efficiency operating conditions, in our design philosophy the GT set is a "RANGE EXTENDER" rather than a prime mover and the traction is purely electric. Thus, the TG operates at its peak efficiency for a limited mission time and is otherwise idling, so that its fuel consumption per km is lower. Consequently, the on-board GT unit acts as a range extender, avoiding the battery packages excessive discharge during the mission and simultaneously supporting the pack in the generation of required peak power. This reduces the required battery installed power, and as a consequence the number of necessary modules.

To identify the most convenient hybridization degree for each type of "mission", the power required by the system is simulated at 1-s intervals. The simulator is set so as to force at each instant of time the difference $\mathrm{Pr} = P_{\mathrm{BT}} + P_{\mathrm{GT}} + P_{\mathrm{AUx}}$ to be equal to zero. The logic implemented in the actual VMU is designed (with obvious safety factors) to manage these energy flows in such a way to allocate the global, instantaneous energy flux among the different components (battery package and mechanical energy storage). Thanks to this "equalizing" effect, the turbine installed power for a city car is less than 10 kW and for a full-size sedan about 30 kW. Since the sum of the various "power output" streams must consistently and exactly make up for the instantaneous propelling power request of the vehicle, the heat engine in our design is smaller than in the commercial configurations (in the Toyota Prius for example the diesel engine is a classic 1900 cc with a nominal output of 90 ÷ 100 kW).

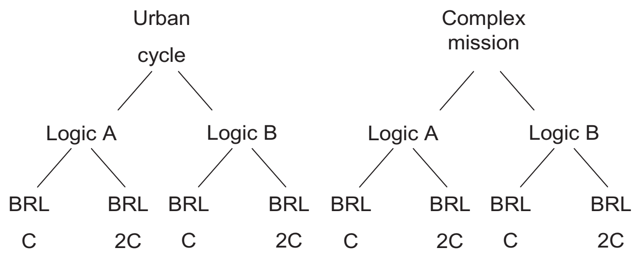

Fig. 1. Scheme of the performed simulations.

4. The mission simulations

Several numerical tests have been carried out to compute the vehicle performance (Fig. 1), in two different driving missions: a combination of 10 consecutive urban cycles ECE15[1] and a "complex driving mission" consisting of 4 consecutive extra-urban cycles EUDC[1] and 72 min of continuous highway drive at 120 km/h. Each mission has been simulated for each of the two concept cars studied here: a "city-car" and a standard passenger sedan. The simulator computes the power balance on the basis of the imposed wheel speed and vehicle characteristics [4,5], and determines the power supplied or absorbed by each system component. This process is repeated at a 1 s interval, assuming that within this time interval, power, speed, and all other significant parameters remain constant. As mentioned above, the GT set is switched on when the SOC is lower than a set point (0.6), and switches to idling or partial load mode when the SOC reaches the maximum set point (0.8). In real operation, a manual override must also be provided, but this was not considered in the calculations. The GT load management protocol is based on the assumption that the currently available small GT sets can operate [13], without substantial efficiency loss, between 70% and 110% of their nominal power. Each simulation starts by assigning the number of modules in the battery package, then the installed power, and finally the GT power: these three values must satisfy the limitations imposed by the above mentioned criteria of maximum power demand, maximum absorbable battery power and minimum allowable SOC [7,9]. The GTs nameplate power was iteratively adjusted until the minimal fuel consumption was obtained. This heuristic procedure was in turn iterated by increasing the number of battery modules, with a consequent adjustment of the total vehicle weight Figs. 2–4. The vehicle design specifications (Table 1) are the same as those adopted in previous papers [5–7].

5. Results of the simulations

Eight different computer simulations have been performed (2 types of mission respectively simulated with 2 types of logic, and 2 types of battery recharge limit BRL).

The final choice of the "optimal" configurations (one for the city car and one for the sedan) is made on the basis of the results of these several simulations, using a heuristic assessment of the respective advantages and drawbacks [10]. The decision parameters are:

- Total gross weight of the battery package (the lesser the better);
- SOC trend during the mission (flat trends are favoured);

[1] EEC Directive 90/C81/01: this is a series of Regulations that prescribe both the emissions limits (adjusted every year) and the methods for testing and qualifying passenger and commercial vehicles. The test driving are in one urban cycle (European Cycle Emission) and an extra urban driving mission (Extra Urban Driving Cycle).

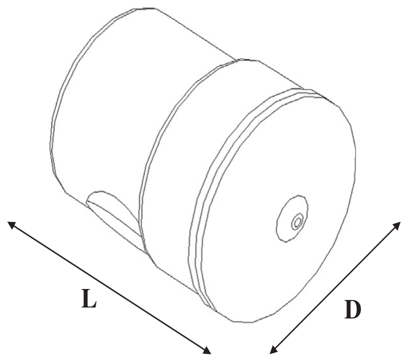

Fig. 2. Asynchronous motor da 30 kW; $L = 315$ mm, $D = 264$ mm.

- Number of GT ignitions during the mission (the lowest possible number is favoured);
- Instantaneous coverage of the total demand power of the vehicle (mandatory);
- Size of the most relevant devices: GT, battery package, flywheel (on the basis of the packaging strategy)

6. Vehicle hybridisation

In the vehicle hybridisation process, once the initial calculations have been completed, each component of the Lethe® vehicle is individually designed according to the procedures outlined in Refs. [1,3,4,7].

For a 30 kW electric motor, the overall dimensions of the main components are reported in Table 2.

6.1. Note about the selection of the gas turbine

The design of the GT units was not a subject of this study, therefore the size and weight of the unit were not expressly calculated. However, in the results presented here, all energy balances were performed on the basis of the known characteristics of the 30 kW Capstone turbo-generator C30HEV [11], and therefore the packaging reflects an excessive size of the turbo-unit, because the optimal degree of hybridization calculated according

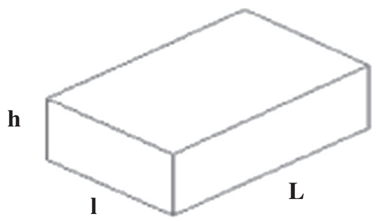

Fig. 3. Inverter; $L = 410$ mm, $l = 340$ mm, $h = 138$ mm.

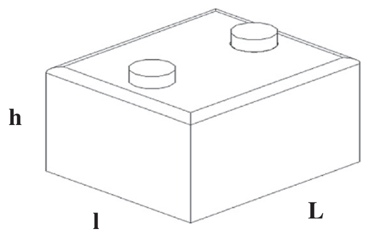

Fig. 4. GENESIS® battery module; $L = 200$ mm, $l = 170$ mm, $h = 170$ mm.

Table 1
GT hybrid vehicle (GTHV) design specifications.

Wheel rolling radius	$R = 0.265$ m
Vehicle width	$b = 1.7$ m
Vehicle height	$H = 1.4$ m
Net front area	$S_f = 2.142$ m^2
Area ratio (S_f/S_{tot})	$\alpha = 0.9$
Aerodynamic drag coefficient	$c_x = 0.25$
Tyre rolling friction coefficient	$f_r = 0.015$
Vehicle mass	$m = 1200$ kg
Equivalent mass	$m_e = 1240$ kg
Air density	$\rho = 1.18$ kg/m^3
Air intake temperature	$T = 300$ K
Minimum SOC	0.6
Maximum SOC	0.8

to the procedures outlined in Section 3 is about 0.25, which corresponds to a 10 kW turbogas set. As an approximate fix, we assumed that -maintaining the same turbine inlet temperature (1300 K) and shaft speed (100,000 rpm) of the C30HEV [11]–the size (measured by the largest diameter of the rotoric case) should be scaled by a factor of 11.32 Such an "ideal" GT group was repackaged as shown in Figs. 5 and 7. Its weight was also evaluated in excess, approximating it to that of a single steel cylinder ($\delta_{steel} = 7.87$ kg/dm^3).

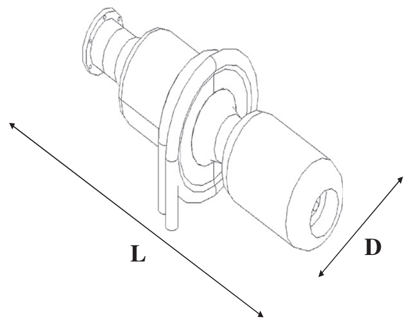

Fig. 5. Gas turbo-generator; $L = 465$ mm, $D = 200$ mm.

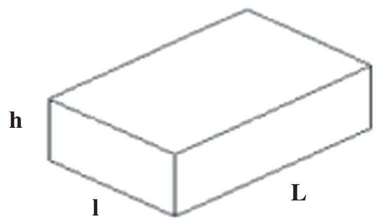

Fig. 6. Fuel tank; $L = 880$ mm, $D = 270$ mm.

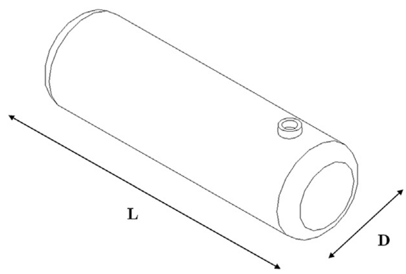

Fig. 7. Regenerator; $L = 340$ mm, $l = 215$ mm, $h = 120$ mm.

7. The LETHE© city car

The weights and dimensions of all components are summarised in Table 3. The battery weighs 78 kg (6 modules) and is placed underneath the rear seats. The gas tank is placed in the aft section while all remaining components are housed in the front section (Fig. 8). This configuration allows a weight distribution of 1432 N (146 kg) on the fore-axle and 912 N (93 kg) on the rear axle, for a 61/39 ratio (Fig. 9).

8. Calculation of emissions for the LETHE© vehicle

Pollutants emissions are linked to several factors (such as the type of fuel, the combustion temperature, the air/fuel ratio), and vary depending on operational conditions. The small amount of emissions data available on TG emissions at off-design conditions refer to large plants, where the combustion characteristics are different (pre-mixer, higher compression ratio), while data for small plants are only available for stationary conditions. As an initial approximation, emissions from the LETHE© under the tested missions were estimated by comparison with emissions from the Capstone turbo-generator C30HEV [11], having presumed that our GT unit has the same inlet temperature in the turbine, same compression ratio and same speed. The Capstone data are expressed in g/kWh and refer to a fuel mass flowrate of 2.36 g/s (Tables 4 and 5).

It was also assumed that the GT unit is regulated by variation of the fuel capacity, maintaining the turbine inlet temperature constant. For this reason, the emissions in the Off-Design operational mode will also be calculated using linear proportionality with emissions at the nominal point of the C30HEV, increased by a 50% safety factor. Table 6 shows the limit values set by the Directive 98/69/CE.

Emissions for the LETHE© city car configuration, on urban routes, are obtained by similar calculations, and are shown in Table 7.

Table 8 shows the percentage reductions of pollutant substances compared to the C30HEV and the EURO 5 Directive.

Such low global values of the emissions are justified by the intermittent use of the GT during a typical mission. On an urban

Table 2
Components dimensions and weight.

Component	Dimensions [mm]	Weight [kg]
Electric motor	Ø264 × 315	80
Inverter	410 × 340 × 138	15
Battery module	200 × 170 × 170	15
GT device	Ø200 × 465	25
Fuel tank	Ø270 × 880	37
Regenerator	340 × 215 × 120	12
Fly wheel[a]	Ø200 × 270	16
Total weight		200 + (16)

[a] The flywheel's task is that of smoothing sharp braking, downward slopes etc. It was sized so as to obtain a compromise between storable energy and volume (Fig. 6). Once the amount of energy that the flywheel had to absorb (20 kJ) and the maximum rotation speed (20,000 rpm) were set, the weight and disk radius were computed using standard formulae [4] (Fig. 7).

Table 3
City car configuration.

Component	W [kg]	Dimensions [mm]
Batt. pack (6 mod.)	90	510 × 400 × 185
E. motor/generator	80	Ø264 × 315
Inverter	15	410 × 340 × 138
GPL fuel tank	37	Ø270 × 880
Fly wheel	3	Ø200 × 270
Fly wheel motor	13	
GT 30 kW	23	Ø200 × 465
Regenerator	12	340 × 215 × 120

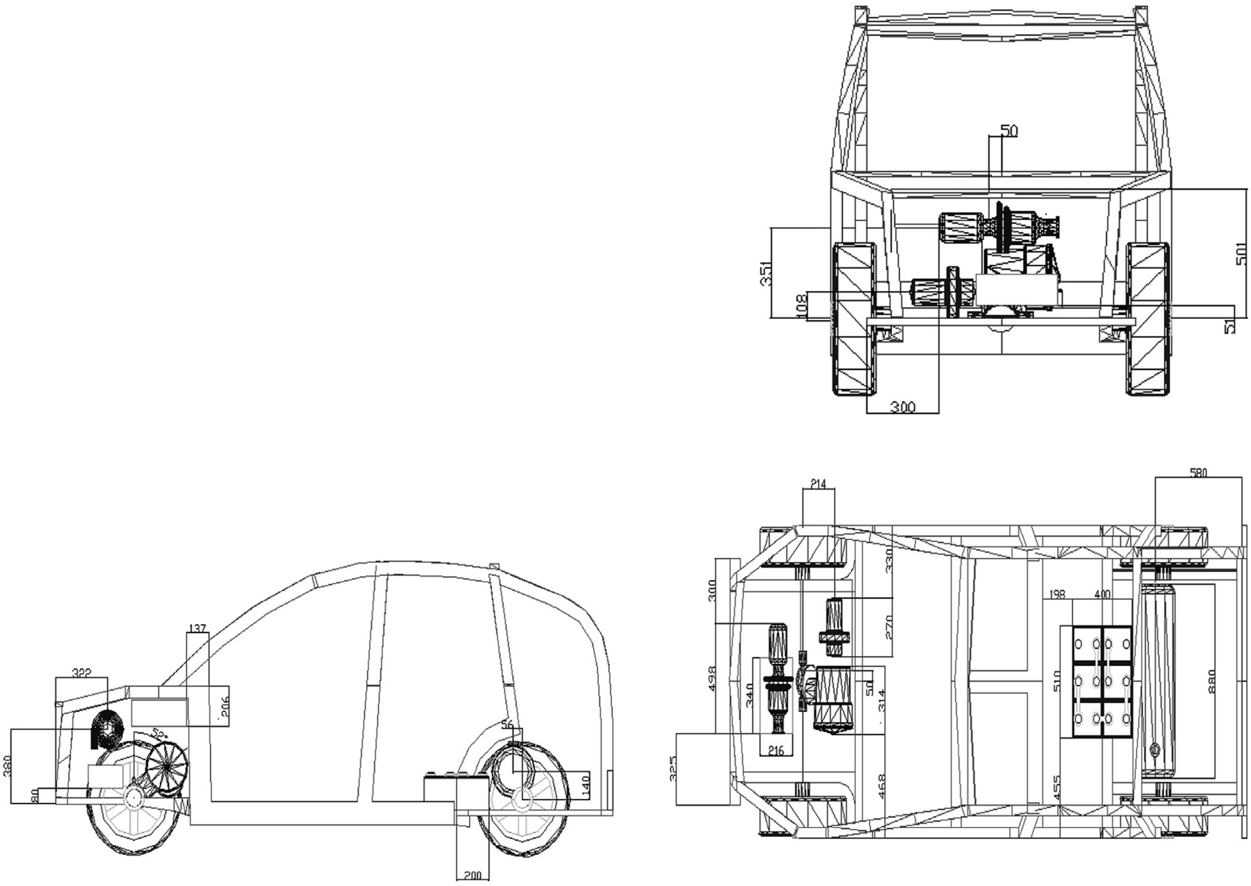

Fig. 8. Views and main dimensions (in mm) of the LETHE© city car configuration.

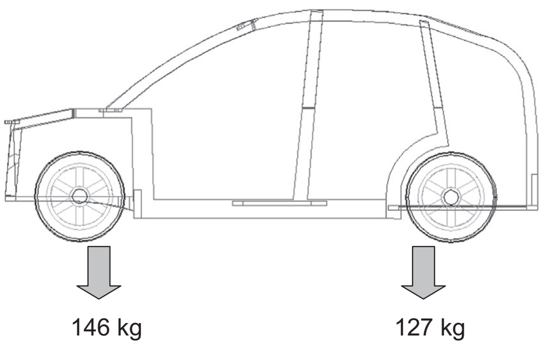

Fig. 9. Weight distribution in the LETHE© city car configuration.

Table 5
EURO directives on emissions.

Normative	NO_x [g/km]	HC [g/km]	CO [g/km]	PM [g/km]
EURO 5	0.04	0.05	0.5	0.0125
EURO 4	0.08	0.1	1	0.025

Table 6
Emissions from the LETHE© city car on urban routes.

Pollutants	Emissions [g/kWh]	Emissions [g/km]
NO_x	5.81E-02	6.18E-03
HC	9.39E-02	9.99E-03
CO	9.17E-02	9.75E-03
PM	9.17E-04	9.75E-05

mission during which 11 km are covered in 1959 s, the GT supplies power for only 440 s (including the time required to recharge the battery package at the end of the mission): therefore more than 75% of the mission is performed in electrical mode. The emissions are calculated on the entire route, considering both the electrical mode and the hybrid mode (GT switched on), and thanks to the net prevalence of electrical drive and to the good efficiency of the recharge train, we obtain the low emissions values displayed in Table 9.

Table 4
Emissions from the Capstone C30HEV unit.

Emissions [g/kWh]	CNG	Propane
NO_x	0.194	0.396
HC	0.313	0.313
CO	0.306	0.134
PM	0.003	0.003

Table 7
Percentage reduction of emissions of the LETHE© city car.

Pollutant	C30HEV	EURO 5
NO_x	−70%	−84.5%
HC	−70%	−80.6%
CO	−70%	−98%
PM	−70%	−99.2%

Table 8
LETHE© data.

Consumption			Pollutants emissions	
[km/l]	[l/100 km]	[g/kWh]	NO_x	−80%
28	3.5	171	HC	−80%
			CO	−90%
			PM	−90%

Table 9
Capstone C30HEV (diesel fuel) emissions [11] at full load and EU limits.

Emissions units	EURO 5 (2008)	EURO 6 (2013)	Capstone C30HEV
	g/kWh		
NO_x	2.00	0.50	0.60
CO	1.50	1.50	1.17
PM	0.46	0.13	0.004

Table 10
LETHE® city car emissions on urban routes and comparison to a commercial city car (SBZ srl 2011 data).

Pollutants	LETHE® city car	Smart
	Emissions [g/km]	
NO_x	0.00618	0.06
HC	0.00999	n.a.
CO	0.00975	EURO V
PM	0.0000975	EURO V
CO_2	75	100

Table 11
Total emissions of a reference fleet composed by 500 gasoline vehicle, with individual annual mileage of 10,000 km and comparison with a Lethe® fleet composed by 500 city cars (same mileage).

Actual commercial fleet	Total NO_x emission, kg/year	Total CO_2, t/year	PM10 total particulate, kg/year
Passenger sedan, gasoline	300	510	n.a.
Total emissions	300	510	n.a.
LETHE® fleet	Total NO_x emission, kg/year	Total CO_2, t/year	PM10 total particulate, kg/year
City car	30.9	375	450
Total emissions	30.9	375	450

The analysis of Table 10 indicates that a turbo-hybrid vehicle equipped with a Capstone 30HEV has lower emissions in comparison with those defined by European directives (in fact, it would satisfy the EURO 6 requirements). The comparison with other current commercial vehicles (Tables 10 and 11) is also favourable for the LETHE©, thanks to the peculiarity of the operational mode of the turbogas group, that is not designed to supply power to the drive train, but to recharge the battery package (range extender) or to complement the battery power during power surges.

9. Conclusions

The technical and economic feasibility of our design for a hybrid passenger sedan "LETHE" has been positively evaluated in previous papers. The most important innovation in this project are the advantages offered by the adoption of a GT in lieu of the traditional thermal motor (i.c.e.). This is not a complete "revolution" in the concept of cars as we know it today, but rather a simple reorganisation of the components. The energy flows management logic (VMU) for a gas-turbine-driven hybrid propulsion system has been previously described in detail [5]: it provides proper operational mode under all driving conditions. The application to possible configurations has been studied, the configurations being differentiated by the presence or absence of the dynamic storage unit (the flywheel) and by different battery recharge modes. All simulations confirm that the LETHE© vehicle is a competitive solution with respect to traditional i.c.e. vehicles and also to other current hybrid vehicles: the calculated fuel consumptions is 29 km/l for urban cycles (compared respectively to 20 km/l for a current diesel vehicle, and 16 km/l for a gasoline sedan [12]). There are also remarkable advantages in terms of weight, size and multi-fuel capacity the GT can be easily adapted to operate with most liquid and gaseous fuels currently available on the market, thus reducing the economic effects of fuel price fluctuations. The analysis carried out in this article is synthetically expressed in Tables 6 and 10, which shows the consumption and emissions of the LETHE© hybrid according to the described procedure. This table contains data obtained both by the simulations discussed in this paper and by previous calculations [6]: it shows a consumption reductions of about 30%, for a methane-powered hybrid city car compared to current commercial vehicles. With regard to emissions, we have highlighted the drastic reduction in all main pollutants emitted from the thermal engine compared to the values prescribed by current regulations, made possible by the optimisation of a thermal motor that operates mostly at design point. It must be underscored that it is the adoption of a Hybrid Series configuration (HS) that makes the use of GT device possible. In a global context of a simultaneous reduction of greenhouse gas emissions, of the consumption of fossil fuels, and of city pollution, it is clear that the benefits introduced by the HS vehicle may provide an immediate response to even the most stringent environmental regulations.

Nomenclature

BP	battery package
BRC	breaking recovery coefficient
BRL	battery recharge limit
C	type of battery recharge limit
DOD	depth of charge
EM	electric motor
GT	gas turbine set
GTHV	gas turbine hybrid vehicle
HD	hybridization degree
HS	hybrid series
HV	hybrid vehicle
i.c.e.	internal combustion engine
IGV	inlet guided vanes
LETHE	Low Emission Turbo Hybrid Electric Vehicle
MTBF	mean time before failure
PM	particulate
SOC	state of charge
UDR1	University of Roma 1
VMU	vehicle management unit

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