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How to improve hybrid vehicles for environmental sustainability. A case study of their impact.

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ABSTRACT

ENEA is studying innovative vehicles such as pure electric and hybrid-electric vehicles, aiming to increase their energy efficiency and to reduce pollutant emissions. As part of such activities, a quite large demonstration project for verifying technical and economical viability of hybrid buses under real public transport operation conditions, has been carried out. Furthermore, a controller for an electric hybrid vehicle has been developed that allows to achieve a further 30% fuel economy improvement. The results of such activities are the input information of the TREMOVE model to investigate the potential impact of electric hybrid vehicle deployment in an Italian city, as a case study. The positive effects of new hybrid vehicle introduction for freight transport in terms of fuel saving and emission reduction, have been also investigated.

INTRODUCTION

In the last 15 years ENEA, the Italian National Agency for New Technology, Energy and the Environment has been conducting advanced research and demonstration programs to reduce the adverse impact of the transportation on the environment and the energy consumption. New transport systems and traffic management tools are being developed and tested to reduce polluting emissions, energy consumption and traffic congestion in major Italian urban areas where poor air quality levels are a daily occurrence. Among others, focus has been directed on: electric vehicles of various types (battery powered, hybrid and with fuel cell generator) characterized by the introduction of innovative components (batteries, fuel cells, supercapacitors and control systems); dedicated large facilities [10, 14] able to test innovative vehicles and subsystems used in European research projects (MATADOR, SCOPE) under different operating conditions; models to verify the design and the effectiveness of control system of innovative vehicles and to evaluate their performances [15]; and quantitative analysis of the overall impact resulting from a large scale deployment of innovative vehicles.

The main framework for ENEA activities was a Program Agreement with the Italian Ministry of Industry. Under this Program, specific testing facilities and technologies have been developed to verify and improve hybrid vehicle performances under controlled conditions (in laboratory) and quite a large fleet of 24 hybrid buses has been tested under real operating conditions.

In this paper is described the research work carried out at ENEA to develop a controller, which would improve the energy consumption and the pollutant emissions of hybrid vehicles. The impact of using such a controller on hybrid vehicles in a city such as Milan has been evaluated by means of the TREMOVE model, a tool able to simulate the transport policy measures in the selected domain to have a quantitative forecast of benefits and drawbacks.

ENEA EXPERIENCE ON HYBRID VEHICLE FLEETS

In the last years, ENEA has sponsored the introduction of series hybrid vehicles and has provided three local public transport companies with 24 hybrid buses produced by the Italian Company IVECO. The hybrid buses were developed by ALTRA (a research company owned by IVECO and ANSALDO RICERCHE) and realized in two versions, a 12 meter and a 6 meter city-bus, both named AltroBus. The 12m city-bus is a modified version of the 490-diesel bus, in which a series hybrid drivetrain has been installed. A small diesel engine powers an electric generator (30 kW DC output power at 600 V) able to charge the lead-acid traction battery pack (with a nominal voltage of 600 V, a storage capacity of 100 Ah, and an overall weight exceeding 2.2 tons) and, jointly with it, to power the traction electric motor (AC asynchronous 3-phase with an output power of 164 kW @ 1500 rpm). The bus has a gross weight of 19 tons and its overall range is about 250 km with about 20-30 km in pure electric mode.

Three cities have been selected for the demonstration: a large city such as Rome, and two medium-size cities, Ferrara (flat land) and Terni (hilly city).

The fleet of hybrid buses has been divided according to the peculiar needs and features of the local public transport company: 12 in Rome, 8 in Ferrara and 4 in Terni where the demonstration was also financed by the EU THERMIE Programme (FLEETS Project) [12]. In all demonstrations, conventional and hybrid vehicles were used in regular public transport service. All vehicles were provided with dedicated real-time data acquisition systems, in order to fully monitor the on-the-road bus behaviour in any working and weather conditions. The experimental campaign lasted about one year.

Table 1 compares the average values of specific emissions of hybrid and diesel buses in Terni. Basically, the hybrid bus fleet demonstration showed significantly positive effects in terms of polluting emission reduction but negligible effects for fuel consumption. Therefore, only a limited interest towards the diffusion of such a technology could be foreseen, especially considering the significant increase of vehicle costs. However, there is a likelihood of significant improvements in hybrid technology achievable with the introduction of new components and a more efficient control strategy, which would increase the appeal for such technology, as shown in the following paragraphs.

Table 1 - Hybrid and conventional bus on-the-road average specific emissions

Vehicle	Fuel Consumption (L/km)	CO specific emissions (g/km)	VOC specific emissions (g/km)	NOx specific emissions (g/km)
EURO II Bus	0.437	5.05	0.82	24.92
Series Hybrid Bus	0.41	0.3	0.59	11.55

HYBRID VEHICLE AND FUEL ECONOMY

Technical works on hybrid vehicles [16] demonstrate that the energy consumption is strongly correlated to the power management strategy. Therefore, in order to maximize the vehicle efficiency, battery losses and DC Source specific consumption have to be considered. Furthermore, the knowledge of the state-of-charge (SOC) of the accumulator is of great importance in the system controller implementation. Therefore, in the framework of the collaboration between ENEA and University of Pisa, a controller for an electric hybrid vehicle, that takes in account such parameters to improve fuel economy, has been developed. The controller is installed on a purpose-designed Light Duty Vehicle, whose hybrid driveline is the same as the 6-m AltroBus. The most important specifications of the hybrid bus driveline are provided in Table 2. The hybrid vehicle was not originally provided of an automatic DC source power control system and its generation system was directly controlled by the driver accordingly to the specific mission of the bus, on the basis of a “on-off” duty cycle.

To acquire information on the vehicle behaviour as a starting point for the controller development, several vehicle experimental tests were programmed at ENEA laboratories. Such tests have been performed simulating the driving cycle of the vehicle on the basis of the ECE 15 urban cycle, which corresponds to the power profile reported in Fig. 1.

Table 2 – Characteristics of 6m AltroBus hybrid vehicle drive-line

Internal Combustion Engine		**Electric Propulsion System**	
Fuel	Diesel oil	Type	Separately Excited DC Motor
Displacement	1204 cc	Rating Armature Voltage	192 V
Maximum Power (@3600 RPM)	24 kW		
Rating speed	2200 RPM	**Storage System**	
Regulation	mechanical	Type	Lead Acid Battery
Synchronous PM Machine		Cells	96
Rating Power (@ 2200 RPM)	10 kW	Capacity (C_5)	100 Ah
Rating Voltage	220 V		

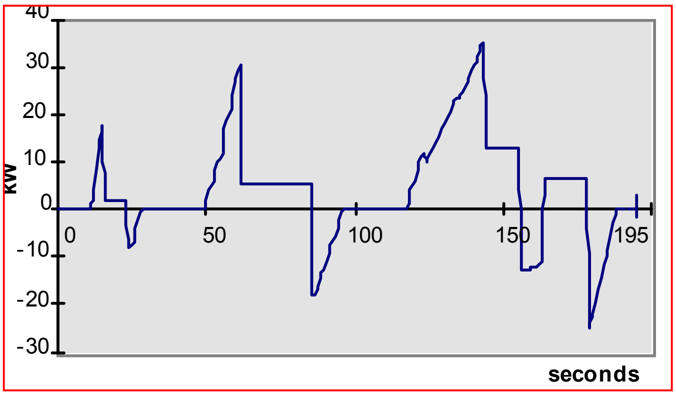


Fig. 1 - ECE 15 power profile

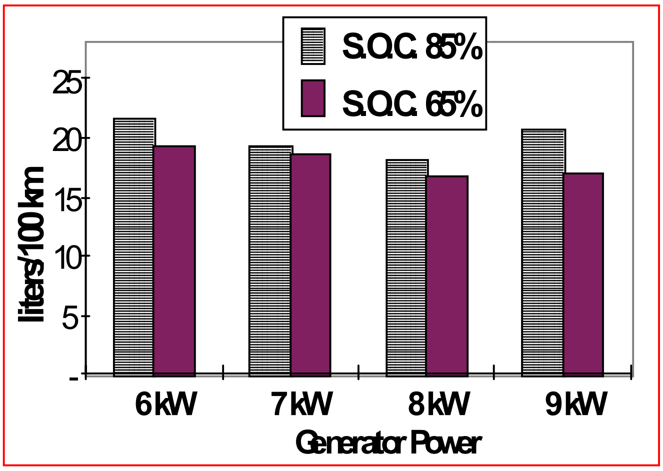


Fig. 2 - Hybrid vehicle fuel consumption

The aim of the tests was to determine the specific diesel fuel consumption of such hybrid vehicle as a function of the battery SOC and the generator power level.

The test confirmed the results of the fleet demonstration experience, i.e. the energy consumption is strongly correlated to the power management strategy, as shown in Fig. 2. The diesel fuel specific consumption ranged from 16.6 L/100km to 21.7 L/100km with an average value of 18.5 L/100 km. The SOC optimum value was found to be around 40%. Larger values did not allow higher fuel economy and lower values were insufficient to drive the vehicle accordingly to the ECE 15 cycle.

THE DESIGN OF THE CONTROL SYSTEM

The main objective of the control system of an electric hybrid vehicle is to provide the power required by the propulsion system while keeping fuel consumption and vehicle emissions as low as possible. Thus, the objective of the control should be the overall minimization of fuel consumption and pollutant emissions.

The hybrid vehicle (IVECO Daily truck) layout is shown in Fig. 3.

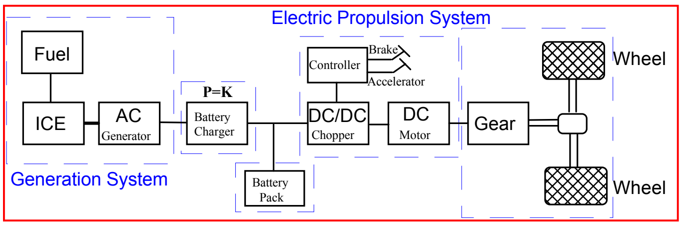


Fig. 3 - Drive-train System layout of Daily truck

The system qualitative power flows are shown in Fig. 4 [1]. The DC source power operates on an on-off cycle at constant power. However the power setpoint can be changed “on line” in a narrow range, ± 20-25%, according to the variations of the control signal P_s*. The battery acts as a power filter, i.e., the DC source delivers only the “average” power requested by the electric drive, and this power can be, for example, averaged every 5-10 min..

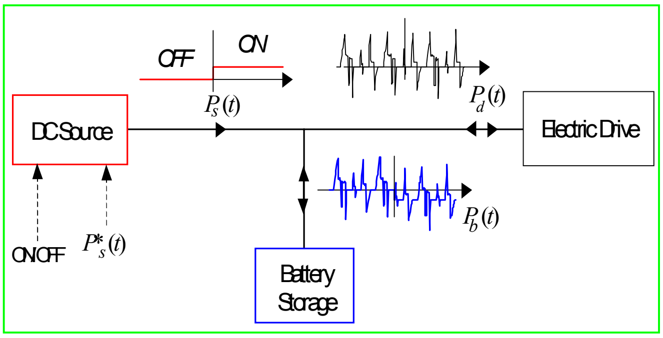


Fig. 4 - Qualitative power flow in the system

From Fig. 4 it is also seen that the requested power to be delivered by the DC source is much more constant than P_d(t). To optimize the operation, the controller logic needs to know the future system load, i.e., the future behaviour of the power demand, at least approximately. Of course the controller does not need a precise forecast of the P_d(t) evolution, but only of its global behaviour; therefore an estimation such as an average value P_d* of P_d(t) in a given forecast interval time, is sufficient.

For the load prediction, the forecast algorithm can use all the available information such as:

- the previous values of $P_d(t)$;
- other information on the trip route (i.e. road slope, traffic conditions, etc.).

The two control variables are the two signals entering the DC source, i.e., the ON/OFF signal and the average requested DC source output power $P_s^*(t)$.

The DC source (see Fig. 3) includes the Generation System and the Battery Charger to convert the alternate current to direct current. Considering different ICE rotational speeds, the DC source specific consumption has a qualitative behaviour of the type depicted in Fig. 5 (upper, black curves).

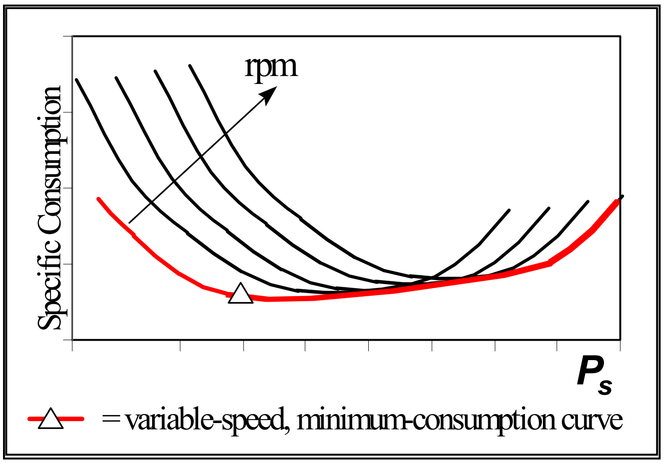


Fig. 5 - DC Source behaviour

If, for each P_s, the optimal speed is considered, the variable-speed specific consumption curve becomes the envelope of minimum points of all the considered curves, i.e., the lower (red) curve in the figure. It is therefore convenient to operate the ICE so that it can follow the red curve, by varying the ICE rotating speed in an interval where the efficiency remains high, whenever the requested power $P_s^*(t)$ is to be provided.

BATTERY MODEL AND ENERGY LIMITS

To define the vehicle control strategy it is important to have a reference model for the lead-acid battery that takes into account properly the SOC variations. To simulate the battery, the simple electrical circuit represented in Fig. 6, can be considered.

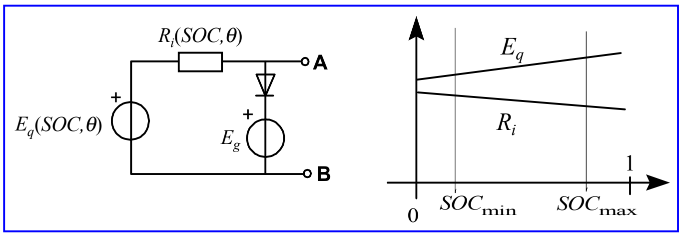


Fig. 6 - The battery equivalent circuit

It is to be noted that both the internal resistance R_i and the electromotive force E_q are not constant during the charge/discharge processes but depend on the state of charge *SOC* and the electrolyte temperature θ. However, for sake of simplicity, linear dependencies of the above-mentioned variables can be considered, as shown in the same figure where R_i and E_q are plotted versus *SOC*.

Such model is utilized for *SOC* on-line estimate and provides an indication of the energy stored in the battery. During normal operation, the battery is operated so that the *SOC* remains constrained within two limits, later called as SOC_{min} and SOC_{max}. In particular:

- SOC_{min} is determined on the basis of the power deliverable by the batteries, which decreases whenever the *SOC* decreases; therefore SOC_{min} is to be chosen with the requirement that the battery is able to deliver the peak power required by the driveline under the worst conditions;
- SOC_{max} is determined on the basis that, at the maximum *SOC,* the V_{AB} voltage does not pass the gas evolution threshold in case of peak power to be absorbed.

CONTROLLER DESCRIPTION

A low cost controller prototype (10-20 $) has been developed at ENEA and installed in the cockpit of the hybrid vehicle IVECO Daily truck (see Figure 7). The device contains a power supply, sensors, relays, etc.. At the present a limited attention has been paid to the dimension of the device but a future industrialized version would certainly be much smaller and cheaper. To be able to follow the transients of an electric vehicle, the controller is required to perform all the computations needed in a short time. A sampling time of 200 ms has been estimated sufficient.

Fig. 7 - The ENEA hybrid vehicle

The present project plan is focussed on developing the control algorithm. The plan foresees that the algorithm can be developed and tested in a step by step way. At the moment, the vehicle uses the simplest version of the SOC controller, so there is no load forecasting and the setting of the power generator is of the “off-line” kind, selected by the driver. The driver also chooses the setting for the initial SOC and its range. The algorithm operates so that the SOC is maintained within the desired range.

TEST CAMPAIGN

The vehicle (see Fig. 7) was tested on the dynamic twin-roll electric dynamometer. Besides the bench equipment, the experimental facility consists of a set of instruments to measure electric parameters such as voltage, current and amount of electric charge, and of a precision equipment for fuel consumption measurement.

The test campaign was performed according to European, American and Japanese urban driving cycles. In this way, the fuel consumption results could be easily compared to the available testing results from all the above driving cycles. The main test results are summarized in Table 3.

Table 3 - Main results of the test campaign

Driving cycle Main parameters	**Unit**	**European Cycle (ECE/NEDC)**	**Japanese Cycle (1015)**	**American Cycle (UDDS)**
Driven distance	Km	28.89	19.80	26.96
Total time	Hours	1h 34’	1h 15’	1h 11’
Average traction power	W	7251	7370	9140
Total traction energy	Wh	11384	9212	10785
Battery charge/depletion	W	7251	7370	5.80
ΔSOC (depletion is positive)	Ah	-1.05	-0.84	4.06
	Wh	-201.60	-161.28	779.52
	Wh/km	-6.98	-8.15	28.91
Fuel oil consumption	kg/h	2.54	2.46	2.68
	Total kg	3.99	3.08	3.16
	Wh	46765	36060	37085
	Wh/km	1618.74	1821.26	1375.59
Equivalent fuel consumption	L/100 km	15.7	17.5	12.5

The Urban Dynamometer Driving Schedule (UDDS) is found to be enough severe in terms of average energy usage to force the hybrid vehicle to a "charge depleting mode" instead of the conventional "charge sustaining mode".

FUEL ECONOMY CONSIDERATIONS

The influence of driving cycles on the energy consumption is clearly shown by the SOC variations.

The SOC is maintained in a range of about 10% of nominal capacity by the ENEA controller in any test with the exception of the UDDS cycle where the final SOC is well below its initial value. The reason is that, in the first part of the test, there is a net SOC depletion, because the generator is kept in the "off" condition till the SOC gets the lower limit of its range, and the vehicle behaves like a "pure electric" vehicle. The consequence is that there is a battery discharge and the SOC cannot regain its initial level at the end of the mission.

However, among all cycles tested, the best fuel efficiency performance was obtained with the same cycle, as the American UDDS average power is the nearest (-2%) to the one provided by the IVECO Daily truck generator. The UDDS cycle is therefore the one that is better interpreted by the dimensioning of the generation system (on a single, specific cycle) that was based on the following condition:

Generator power = Average traction power **(1)**

From the SOC diagram in Fig. 8, which results from the American cycle tests and oscillates around 74 %, it can be seen that the battery-motor power flows are only correlated with the variation of the traction power during the mission. In simpler words, there is no net battery charging or discharging after the initial phase. The positive consequence is that the SOC variation range is self-reduced, without any diesel engine starting and stopping.

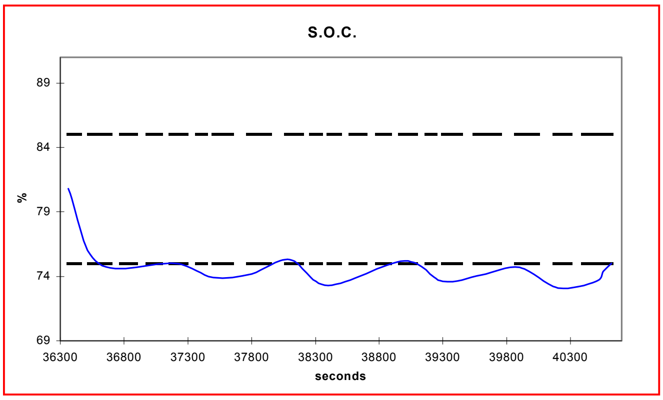


Fig. 8 - SOC trend during UDDS cycle

As a conclusion, a reduction of the fuel consumption can be foreseen by implementing the control system installed on the vehicle with a periodic load following additional function. The next version of the controller algorithm will include a periodical check of the condition (1) to adjust the generator power set to the cruise condition.

The load following could create some difficulties in terms of allowing the generator engine to work within the domain of efficient operation, especially if such a domain is not sufficiently extended and/or the control algorithm is not enough sophisticated to utilize completely the optimal domain. It must be considered that, to obtain on the European cycle the same behaviour of the American cycle, the thermal engine would have to be set up to work at reduced power of 7 kW, but with a specific consumption equal to the one achieved at the highest power (9 kW) of the American cycle. Hence the necessity of a more sophisticated generation group management, which has to control not only the load, but also the rotational speed of the generator thermal engine.

In conclusion, the improvements that can be achieved under such assumptions for the European cycle can be derived through a simulation [1,2], that shows a consumption of 13 L/100 km, with the same hardware and batteries. Another way to achieve similar results can be followed, by using an energetic analysis. To this end it is useful the definition of efficiency η:

$$\eta = \textbf{\textit{(total traction energy) / (equivalent fuel consumption)}} \qquad \textbf{(2)}$$

As a matter of fact (see Table 3), the equivalent fuel consumption during the European cycle was 11384 Wh, the total generated energy 46765 Wh, the efficiency :

η_{ECE} = 24 %

During the UDDS, the total traction was 10785 Wh, the equivalent fuel consumption 37864 Wh (also considering the SOC depletion), and the efficiency :

η_{UDDS} = = 29 %

With the same efficiency, the equivalent fuel consumption in the European cycle would be :

11384/0.29 = 39255 Wh

instead of 46765 Wh, corresponding to 3.27 kg (or 3.89 L). Considering the total driven distance of 28.9 km, the equivalent fuel consumption would be reduced to 13.5 L/100 km, vs. 15.7 L/100 km of the conventional type one (-14 %). This result corresponds to the one calculated for the Mitsubishi HEV, whose efficiency, on the Japanese urban cycle, is expected to improve from the 9.2% for current vehicle, to a 14.3% for the HEV [3].

Fuel economy could increase even more and a consumption less than 30%-40%, respect to the conventional vehicle, could be achieved if a diesel engine, with a specific fuel consumption comparable to the 2.5 litres DI diesel used on the conventional version (210-220 g/kWh vs. 270 g/kWh of the IDI used on the hybrid), and better batteries ($\eta_{ch/dsch}$ = 0.8 vs. 0.7) were introduced on the hybrid.

HYBRID VEHICLE DEPLOYMENT CONTEXT

After having demonstrated that the hybrid vehicle technology is useful, the focus is to be addressed on the impact of such technology on a large-scale application in order to substitute the old internal combustion engine vehicles thus avoiding or reducing their related noxious effects. Of course this implies that a significant market share, although at a niche level, could be associated to the hybrid technology deployment in a way that its effects can fully detected.

With this in mind, the first issue is to identify a correct field of application for hybrid vehicles with the constraints that the experience effects should be detectable at a global level. To this end, a rapid answer can be provided by restricting the application to the urban domains. This has relevant advantages: allows to better monitor the results of the experiences; reduces the investments to be made; is of general applicability as the experience can be easily transferred to other urban domains; and does not require the deployment of many infrastructures.

THE FRAMEWORK OF THE STUDY

The city of Milan was selected as framework, since it has been considered the reference Italian city under AUTOIL II Programme carried out by the European Commission, together with the car makers, the oil industries and the Member States. The scope of AOP II, which was completed in the year 2000, was to provide an assessment of the most effective policies for the transport sector (mainly for the road transportation), to improve the air quality level by reducing the concentration of noxious pollutants. Air quality targets have been defined by the Air Framework Directive (96/62/EC) and its related Daughter Directives enforced over the entire European Union territory.

Under AOP II, sophisticated simulation tools have been developed. They allow to make a quantitative assessment of the provisions and to check that the forecasted pollutant concentrations are not providing damages to the human health and to the ecosystem in general. Besides, they allow the selection of the most effective provisions, i.e. the ones at the minimum cost. Among such tools is the TREMOVE model [4,5,6] that gives the forecast of the transport policy effects in terms of vehicle emissions and costs of the transport, that depend on the mode under consideration, the cost of the travel time, and other elements such as taxes and incentives on vehicles, fuels, etc..

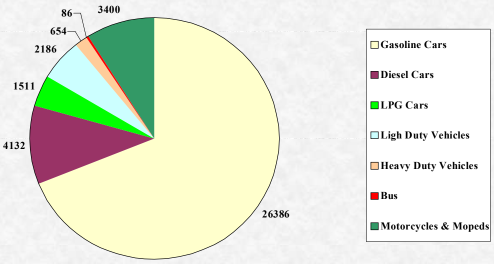
Among the polluting substances taken into consideration by the model are carbon monoxide (CO), nitrogen oxides (NO_x), volatile organic compounds (VOC), benzene (C_6H_6), particulate (PM_{10}), sulphurous dioxide (SO_2), methane (CH_4), carbon dioxide (CO_2), other greenhouse gases, etc. The list of substances includes all the pollutants considered by COPERT methodology [7, 8], which is embedded into TREMOVE. The model needs as input information the provisions to be studied and predicts the transport behaviour for a selected time interval. The tool begins its processing from an aggregated level of the transport demand for people and goods and determines how the policies would act on such a demand. The transport demand is split among the available transport modes (road, railway, ship) and the related public and private categories (e.g. for the private road transport mode many categories exist, such as different typologies of cars -further subdivided on the basis of fuel and engine size-, of motorcycles, etc.). The modal split is carried out by calculating the cost of each transport mode and selecting each modal share on the basis of its marginal cost.

The following step is the evaluation of the resulting traffic conditions, i.e. the speed and the load factors for the vehicles considered, through a simplified congestion function. The transport demand is an important item for the forecast of the vehicle fleet, which also depends on some specific provisions (i.e. scrappage policies, selective taxation, etc.). The forecasts of vehicle fleet composition and usage, together with the vehicle speed, are the parameters that allow the calculation of emissions and fuel consumption. The fuel consumption, together with the vehicle fleet composition, is then used for a new iteration until the convergence criteria are met.

THE TECHNICAL AND TERRITORIAL CONTEXT

The next issue is related to which type of hybrid vehicles are suitable for a large-scale experience and how to proceed. Also for this item an answer can be provided by looking at the field of the urban freight transport. Presently, goods are delivered in the urban context mainly by Light Duty Vehicles, fuelled both by gasoline and by diesel. This is a consequence of the structure of Italian towns that are characterized by narrow roads and the presence of historical buildings. Therefore, the use of Heavy Duty Vehicles is very difficult for accessibility and environmental reasons. However, some other insights are required in order to consider if the proposal to use series hybrid LDVs for freight transport is technically sound and is applicable to large-scale urban deployment. To this end, it is useful to overview the Italian situation. In Italy [9], the main share of the freight transport (about 70% in the year 1998) is covered by road transportation. This includes both urban and extra-urban transport. Another important item is the national road vehicle fleet, whose composition in thousands of vehicles at the end of the year 1999 [11] is shown in Fig. 9. It can be seen that LDVs correspond to about two millions of vehicles, of which 1.8 millions use diesel fuel and the remaining ones gasoline. This corresponds to a share of some more than 5% of the Italian fleet. Data belonging to Milan province show that, at the same date, the LDVs registered in the province were about 142 thousands.

Fig. 9- Composition of Italian vehicle fleet (end of year 1999)



Of course, this does not allow to consider that the only LDVs travelling through the city of Milan are the ones above indicated, but gives an idea on what is the number of vehicles to be taken into account for the deployment analysis. The above mentioned data on fleet composition confirm the idea that looking at LVDs for their introduction on a niche market such as the one of urban freight delivery, can be viable as the amount of vehicles to be replaced is not very high.

On the other hand it is important to evaluate if the application of such vehicles in an urban area may have detectable effects by providing sensible reduction of the urban environment pollution. An answer to this question is given in Fig. 10, where the impact of LDVs for the city of Milan is shown. The data are derived by the AOP II Italian reference scenario and are related to the year 2000.

From the diagram it is clear that LDVs contribute significantly to all main road transport pollutants. In particular, the shares of PM_{10} and SO_2 are very high, respectively of 29 and 14%.

Thus the questions are: is it feasible to build hybrid LDVs and do they allow reductions of the road transport impact? Some of the answers have been already provided, but some other considerations can be drawn.

From the technical point of hybrid LDVs can be designed more easily than passenger cars, as they can be more flexible in order to allocate the volume required by the additional equipment (electric motor, batteries, etc.).

However, to evaluate their real effectiveness, it is necessary to compute their specific emissions according to COPERT. It has to be underlined that COPERT correlations are based on the information coming from the tests of existing vehicles and therefore, strictly speaking, they are unable to predict the behaviour of future vehicles. To overcome this problem in EURO III and EURO IV standards (applicable to the ICE vehicles on the market as of 2001 and of the 2005 respectively), the related emissions are calculated adopting some reduction coefficients, applied to the emission values of the equivalent EURO I vehicles. It is also necessary to observe that the reduction coefficients should have been determined by adopting conservative criteria; therefore, whenever such vehicles were widely available on the market, emission values equal or smaller than those obtainable from the calculation could be observed for them.

Similar considerations can be applied to compute the hybrid vehicle specific emissions. Additional reduction coefficients can be considered in order to reduce the forecasted vehicle emissions, whenever they are deployed in a significant share. It is easy to justify this as the hybrid vehicles would have the same engine of ICE vehicles (Euro III and IV), but working in a more controlled domain where a better efficiency can be achieved. In particular this assumption holds, whenever the driving conditions change rapidly and stop and go situations are frequent. Even in the off-peak hours, the presence on the road of pedestrians, traffic lights, junctions, vehicles searching for parking, etc. require continuous adjustments of the vehicle speed. Therefore, in urban areas several accelerations and slowdowns are required, causing the engines of the presently available vehicles not to operate at their most efficient working point. This could be avoided or at least reduced in a hybrid vehicle with the help of a control system that constrains the thermal engine to work in a very efficient interval, so providing significant improvements of specific consumption and emissions.

The problem is now to determine the reduction factors to consider. To this end, the indications coming from fleet tests made in Italy (see Table 1) are very valuable [12,13]. The large improvement on the field specific emissions of the hybrid bus justifies to consider consistent emission reduction factors. In practice, values such as the ratio of the measures shown in Table 1 can be assumed. Furthermore, the hybrid buses tested in Terni were not provided of any control system while such option is considered for this analysis, thus increasing the engine efficiency and reducing the emissions. Therefore the same reduction factors used for HDVs can be considered for the LDVs emissions. For gasoline hybrid LDVs no field data are available; therefore it is safer to use higher factors as they act in the conservative direction. Looking at fuel consumption, the previous analyses show that there are consistent margins to increase the efficiency. However, to be in the conservative side also in this case, a fuel consumption reduction of only 10% has been considered for any LDVs. The consumption and emission reduction factors as reported in Table 4.

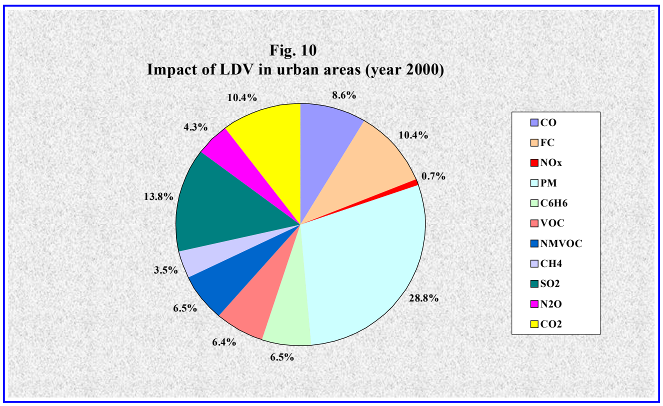


Fig. 10
Impact of LDV in urban areas (year 2000)

Table 4- Hybrid LDVs reduction factors

Indicator	**Reduction factor**	
	Gasoline LDV	Diesel LDV
CO emission	0.7	0.1
NOx emission	0.7	0.5
VOC emission	0.7	0.7
PM emission	1.0	0.6
Fuel consumption	0.9	0.9

The use of the above factors allows the computation of hybrid vehicle specific emissions as a function of the average speed according to COPERT approach. To have an idea of the speed behaviour the histograms in Fig. 11 and 12 are provided, respectively for fuel consumption and CO specific emission.

It is interesting to observe that in the fuel consumption histogram there is an increase of fuel values for EURO IV vehicles, as the new targets on pollutant emission have required the introduction of additional devices that lower the vehicle fuel efficiency.

THE HYBRID LDVS SCENARIOS

It is now possible to evaluate the effect of the introduction of LDVs in the city of Milan. The main hypothesis is that from year 2002 a growing portion of the new LDVs, purchased in the city, is based on the series hybrid technology. In the scenario it is assumed that the hybrid LDV share would be 20% for year 2002, 55% for year 2003 and 100% for year 2004 and the

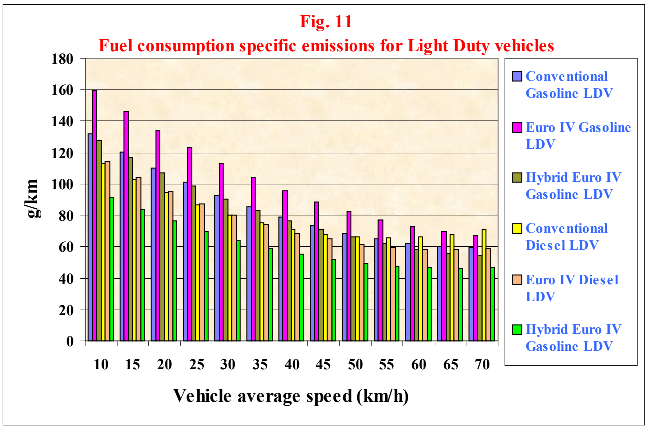


Fig. 11
Fuel consumption specific emissions for Light Duty vehicles

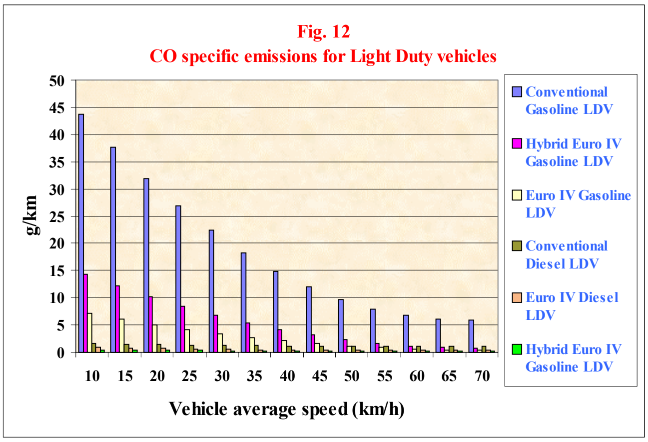


Fig. 12
CO specific emissions for Light Duty vehicles

following years. Although the introduction of the hybrid vehicles could appear too fast, such time interval allows both the industry to be able to provide the vehicles and the users to become acquainted with the new technology. In particular for the year 2002, only 2000 hybrid LDVs are required and this could be handled by the industry. On the other hand, it is to be stressed that, to provide consistent benefits, the new technology needs to replace a considerable share of the entire fleet and this can be achieved only if there is a strong boost toward the substitution of the scrapped vehicles with the innovative ones.

The emission reduction in the city of Milan, evaluated through the use of TREMOVE is summarized in Fig. 13. The main benefit of introducing hybrid LDVs would be on the particulate reduction, whose emission is cut of about 5%. In fact LDVs are responsible for a high share of this pollutant and therefore the substitution of old and dirty vehicles with the hybrid ones plays an important role. In any case for all the indicators there is a growing benefits that stabilizes at year 2008, whenever almost all of the oldest vehicles have been replaced.

The effect of the substitution of conventional LDVs with hybrid ones can be also investigated in the direction of increasing the delivery efficiency by creating an assistance framework that can co-ordinate the freight transport. This could be achieved by providing the city with a logistic system that is able to assign the loads to different vehicles to optimize the goods delivery. The availability of such a logistic system could provide consistent savings in terms of total mileage, travel time, fuel consumption, etc.. Presently telematics technology has the full capability to help consistently the freight transport in this direction. The assistance can be performed both at the trip planning phase by creating the optimal load filling for the LDVs fleet, and at the delivery phase where, for instance, indications on the best routes could be provided to each vehicle in real time.

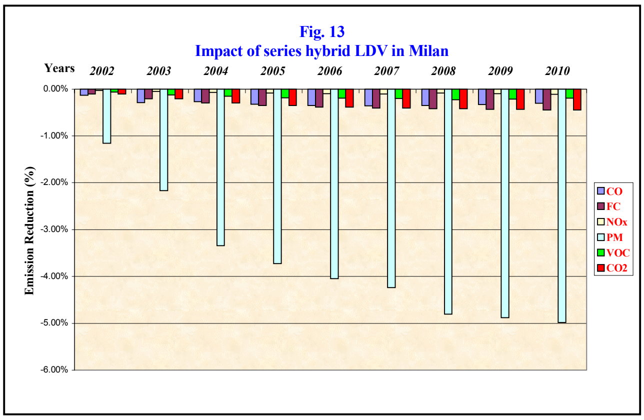


Fig. 13
Impact of series hybrid LDV in Milan

Of course it is not easy to simulate such a scenario, that has been analyzed only by increasing the average load of the vehicles. The results are provided in fig. 14, where it can be seen that the benefits in terms of emission and consumption reduction are very relevant. Such feature can be also applied to conventional vehicles, but it could be implemented in an easier way on the hybrid vehicles, as they could be designed taking into account such requirement, in order to make them fully compatible with the logistic system.

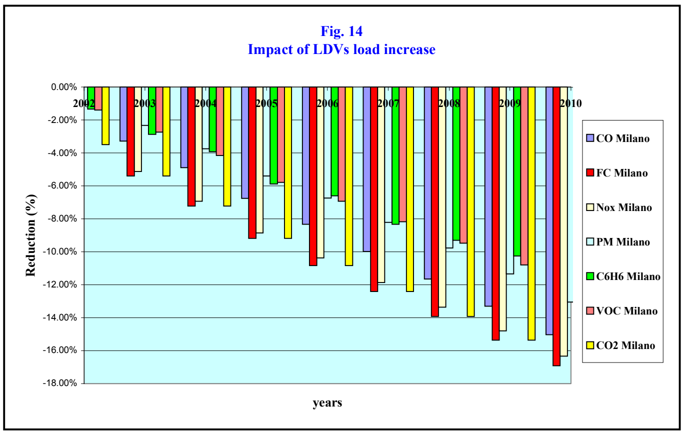


Fig. 14
Impact of LDVs load increase

The increase of vehicle load factor implies as natural consequence the reduction of the total LDVs annual mileage. Therefore in the urban area two environmentally positive effects will be seen, i.e. the direct effect provided by LDVs and an indirect effect by the other vehicles. By reducing the number of LDVs vehicles on the road, there will be better traffic conditions with an increase of the average speed. This effect will be beneficial as shown by COPERT correlations that generally provide lower emissions at higher speed.

This scenario clearly shows that the vehicle technology improvement could be much more effective if other synergic provisions are added. To this end, there is a wide variety of provisions that could be taken into consideration. Among them there are road pricing, scrappage incentives, etc. Another interesting item to be considered is that through the selective introduction of hybrid vehicles, the citizens will become familiar with the technology and other important markets could be opened to it, i.e. buses, passenger cars, heavy duty vehicles, etc.

To have an idea of the additional costs connected to the hybrid LDVs deployment it is easy to understand that the major impact will be in the first years, where scale economies on vehicle production are very difficult to be met. After this initial period the LDVs cost will decrease as a consequence of the significant industrial production of such means. Considering the time interval from year 2002 to 2005 in Milan under the scenario hypotheses, about 29 thousand hybrid LDVs would be deployed in Milan. Therefore, considering an extra-cost of about 30% for each LDV and an average cost of about 20 kEuro the additional cost will be of about 174 millions of Euro. It is to be underlined that the total investment is distributed in a period of time of four years and, for the first year, the extra-cost is 12 millions of Euros, as only 2000 hybrid LDVs are deployed.

The total extra-cost is quite high but can be afforded, especially if the target city for a practical hybrid LDVs deployment would be a smaller city. In such a case the investments would be dramatically reduced.

CONCLUSIONS

In this paper the viability of the series hybrid vehicles has been considered in order to understand what are the benefits that can derive by their use. Laboratory experiences carried out at ENEA Casaccia and fleet experiences demonstrated that high emission and fuel consumption reductions can be obtained with respect to conventional vehicles. This can be achieved if some improvements are added to the present vehicles. In particular the development of an automatic control device has been carried out for a prototype hybrid vehicle.

To this end, a campaign of tests on the vehicle without the controller has given the reference information in order to evaluate the possible benefits of the control system. In particular, an average consumption of 18.5 L/100 km has been measured. This means that an equivalent conventional vehicle, having a consumption of 16 L/100 km, is better of the uncontrolled hybrid.

The second campaign of test, with the controller installed on the vehicle, has improved the situation with the consumption of the hybrid being similar to the best one of the values found in the first set of tests. In this campaign better specific consumption has been found especially on the American cycle, that represented the heaviest cycle considered.

A computer simulation and an energetic analysis have shown that the load following implementation on the control system allows to reach a specific consumption of 13.5 L/100 km versus 15.7 L/100 km of the conventional version (-14%). If a diesel engine, with specific fuel consumption comparable to the 2.5 litres DI diesel used on the conventional version and better batteries, should be introduced on the hybrid, fuel economy could increase even more.

Starting from these results, the possible impact of a quite large-scale hybrid LDVs deployment has been analysed for the city of Milan. The driving criterion adopted for the choice of Milan was the availability of already configured forecast tools and high quality data. This has contributed positively in speeding up the analysis and has also made possible to compare the results with a reference scenario, i.e. the “business as usual” reference scenario created under AOP II. Besides Milan indications can quite easily be transferred to any other city, where the deployment of hybrid LDVs is considered useful. The results have shown that the hybrid technology can give a positive contribution especially for the reduction of harmful pollutants, as the effect on the fuel was minimized by the use of very conservative factors. In particular the positive effects are strengthened by adding some non-technical measure to the hybrid vehicle deployment. To this end the only hybrid LDVs introduction shows that the main improvement is a reduction of 5% of PM, while, if some logistic measures are also added, almost all the indicators show positive effects.

However, the paper has not addressed some important aspects related to the introduction of the new technologies into the market. Up to now the main efforts in this direction have been concentrated on promoting experiences, where fleet tests of a few innovative vehicles have been carried out. Of course this is an important step, but other very important issues such as legislation, lack of infrastructures, user information, etc. have been neglected.

Presently this is one of the most important reasons for the poor presence of the innovative vehicles in the overall fleet, although relevant investments have been made in the last years.

In conclusion, the analysis has shown that the technology can push for the improvement of the environment and for fuel consumption reduction, but by itself it is unable to reach all the targets and can benefit of other provisions.

In fact, the transport problems are to be solved by considering that three main items, each other interacting, are to be considered: the vehicles, the infrastructures and the users. Therefore the transport solutions must be always found considering all these three items and this rule is to be considered also for the hybrid technology deployment. In any case the hybrid technology can contribute to provide viable, durable and sustainable solutions to the transport problems.

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ACRONYMS

ICE: Internal Combustion Engine

DC: Direct Current

AC: Alternate current

SOC State Of Charge

HEV: Hybrid Electric Vehicle

DI: Direct Injection

IDI: In-Direct Injection

HDV: Heavy Duty Vehicle

LDV: Light Duty Vehicle

AOP: Auto-Oil Programme