A plug-in hybrid electric bus fleet as a rational and sustainable urban transport policy: a real casa application in Italy

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Abstract: Urban sustainability, green development and sustainable mobility are based on the achievement of three goals: environment, society and economy. This means that a sustainable planning must be, at the same time, equitable, viable, and bearable. In metropolitan areas, the transport sector impact with respect to both fuel consumption and environmental emissions. At this aim, planning policies aimed at reducing these negative impacts are very important. Many researches cover the problem of perform rational decisions to improve the transportation sector. A rational decision means acting in the best possible way considering the goals and constraints. Starting from these considerations the aim of this paper was investigated the energy and environmental implications deriving from the renewing of public transport bus fleet to both electric and diesel plug-in hybrid vehicles. The case study was the city of Salerno in Italy. Results of the estimation show that the renewing the 30% of the bus fleet into electric vehicles will produce significant positive environmental impacts, but the high investment costs suggest that this policy is not "eco-rational" for the city because of it is not economically convenient form a cost-benefit point of view. By contrast, the renewing of a percentage of the bus fleet into a diesel plug-in hybrid electric vehicle will produce comparable environmental impacts to those estimated for the previous design scenario, but in this case also the economical sustainability was verified with an investment payback period equal to 10 years.

Key-Words: urban sustainability; green development; sustainable mobility; clean transport; transportation planning; sustainable mobility; greenhouse gas; particulate matter emissions; fuel consumption; ex-ante evaluations; cost-benefit analysis.

1 Introduction

Urban sustainability, green development and sustainable mobility are based on the achievement of three goals: environment, society and economy. This means that a sustainable planning must be, at the same time, equitable, viable, and bearable. In metropolitan areas, the transport sector impact with respect to both fuel consumption and environmental emissions. At this aim, planning policies aimed at reducing these negative impacts are very important. Many cities are adopting urban plans aimed to both a green development and a sustainable mobility (e.g. [1], [2], [3]). These solutions, as discussed in [4], are very different both in terms of impacts (benefits) and in term of implementation costs, and the overall effects are often difficult to anticipate on a purely intuitive basis and sometimes the final effect could be the opposite as the expectations (e.g. policies aimed to reduce traffic emissions, ending in increasing them).

Many researches cover the problem of perform rational decisions to improve the transportation sector (e.g. [1], [4]). A rational decision means acting in the best possible way considering the goals and constraints. The authors in [1] define some "*minimal requirements of rationality*": the decisions must be comparative (more than one alternatives must be compared); aware of the impacts derived from the plans implementation in term of costs, benefits, risks and opportunities; consistent, design comparing alternatives with the goals and the constraints; flexible because the future is unknown, and the context is unpredictable.

As suggested in [4], [5], the idea is to prefix the term "rationality" with the acronym "ECO". ECO-rationality in a rational urban planning means "acting in the best possible way considering the men's health and the environment's benefits and are sustainable for an economic point of view". Starting from this consideration, are always the "traditional" sustainable transport strategies eco-rational? E.g. the renewal of car fleet; the use of light freight vehicles for city logistics, the introduction of a limited (restricted) area in urban context, are always rational

policies as defined before? In this paper some possible answers were proposed on this topic, quantifying the environmental impacts in using plug-in hybrid electric buses for public transport services. The case study was a medium size city in Italy.
In this context, the quality (e.g. [6], [7], [8], [9]) of the mobility policies proposed cover an important role in improving urban sustainability in term of energy and space-efficiency
With respect to these aims, the ex-ante evaluations (through quantitative methods) could improve a sustainable urban mobility (eco-rational transport planning). With respect to vehicle emissions and energy consumption models, the state of art propose different mathematical models (e.g. a state of the art was proposed in [10] and [11]), that allow quantifications of average concentrations of pollutants in function of travel demand (e.g. vehicle fleet composition, average paths length) as well as traffic flow conditions (e.g. vehicle speed and/or density). The most common approaches applied are often aggregated and the input variables were estimated through mobility surveys (e.g. [10], [11], [12], [13]).
Jointly with papers dealing with the problem of emission and consumption estimation, there is a copious literature regarding the best practices in term of both ex-ante and ex-post evaluations. Even if the quantitative methods for the ex-ante evaluation (e.g. [16], [17], [18], [19]) cover a central role in rational sustainable transportation planning (e.g. [1], [2]), there are also several applications aimed in ex-post analyses (e.g. [14], [15]).
Starting from both from these considerations and from the results of a previous works [10], in this paper was investigated the energy and environmental implications deriving from the renewing of public transport bus fleet to both electric and plug-in hybrid vehicles. The case study is the city of Salerno (Italy).
The paper is structured into three sections; first the proposed methodology is discussed; then the case study application is detailed, while finally the main results and conclusions are reported.

2 The applied methodology

The methodology proposed for the case study discussed in the next section derive from the ones proposed in [10]. Precisely, the authors in [10] proposed an integrated framework which combines an emission and fuel consumption traffic model with a transportation simulation model (demand, supply and assignment models).

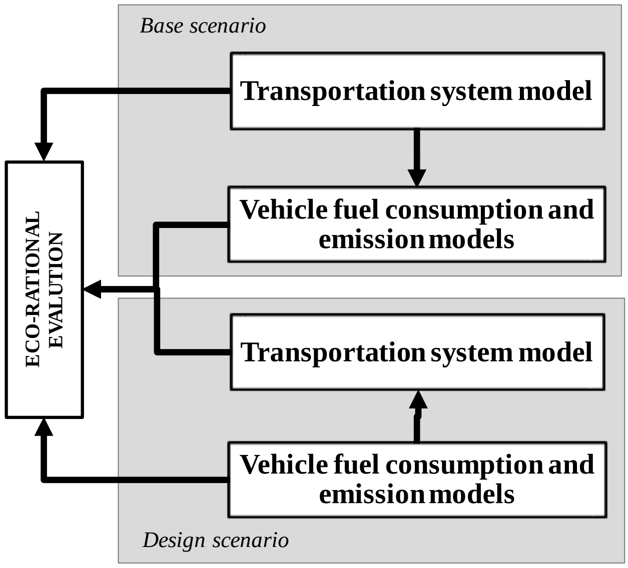

Fig.1 – Estimation methodology

Emission and fuel consumption traffic model allows to quantify the effects of design scenarios, while transportation model allows the estimations of performance indicators (e.g. average speed and distance travelled by each vehicle category) regarding both a base scenario and some possible design scenarios.

The transportation system model was composed in sub-models (e.g. [20], [21], [22]):

a) network supply model;
b) demand models;
c) assignment model.

All the applied simulation models are based on consolidated transportation system approaches (e.g. [23]).

The emission and consumption model proposed was:

$$T_{ijk} = TF_{ijk}\,(Sp_{jk}) * Veh_j * KM_{jk} \qquad (1)$$

where:

T_{ijk} = is the total annual emission/consumption of the pollutant/fuel i for vehicle type j, on the path travelled k (tons / year and pet / year);
TF_{ijk} = is the emission/consumption unit factor of pollutant/fuel i for vehicle type j on the path travelled k (grams / km);
Veh_j = is the vehicle fleet composition (the number of vehicles related to the category j);
KM_{jk} = is the average annual mileage related to the vehicle type j on the path travelled k (km / year);
Sp_{jk} = is the average speed related to the vehicle type j on the path travelled k (Km / h).

The COPERT is the software used for the estimations. The pollutant considered were: CO, NOx, VOC, SO2, CO2, PM10, while the fuel categories used were: gasoline; diesel; Liquefied Petroleum Gas (LPG), while for the goods vehicles were: light goods vehicles (gasoline and diesel); heavy goods vehicles and buses.

This methodology was applied with different levels of spatial and temporal aggregation. For example, it was applied for estimating both the annual regional emissions/consumptions level and for daily urban estimations.

The model output are the concentrations /consumptions of a wide range of pollutants/fuels resulting from combustion and evaporation of the fuel used by vehicles. The more accurate are the input data, the more reliable are the estimations results.

3 Application case study

The application case study is Salerno municipality – ITALY (Fig.2). This city is in southern of Italy. It has a population of more than 138 thousand with an average GDP of 3.4 million of euro/year. The supply model consists of a road network with about 540 nodes and about 1.2 thousand links ([24]). The generalized transportation cost (disutility) associated to each road link was estimated as the result of a sum of two terms: the vehicle running time (using the function proposed in [25]).

Fig.2 – The application case study: Salerno city in Italy

OD demand flows were estimated through transportation discrete choice models.

Furthermore, traffic counts and some other aggregate origin-destination demand flows counted were also used to update demand estimations (see [26]). For more details on the models characteristics see [27] and [24] for passenger demand models (car, motorcycle and bus), while [28] and [29] for freight vehicles demand (goods vehicles).

The proposed methodology was applied for different vehicle categories *j* in term of vehicle, fuel type and ECE regulation characteristics of the vehicular fleet.

Through the proposed methodology the overall urban fuel consumption was quantified (Tab1, Tab. 2 and Fig.3). In Salerno the gasoline consumption is about 12,000 tons/year while diesel consumption amounts to about 27,000 tons tons/year. These consumptions are equivalent to 43,000 pet/year (equal to 0.3 pet/year per inhabitant), where "*pet*" is the *petrol equivalent tons,* estimated through the Global Warming Potential (GWP) coefficients.

Tab.1 – Estimation results: vehicle composition and consumptions

Vehicle category	cars	motorcycles	buses	HGVs	LGVs	Total
Number of vehicles	79,400	18,800	570	1,650	8,500	108,850
Diesel consumption (tons/year)	6,800	-	9,500	7,800	2700	26,700
Gasoline consumption tons/year)	10,200	1,000	-	34	340	11,650
Total consumption (pet/year)	19,600	1,200	10,300	8,400	3,300	42,80

Tab.2 – Estimation results: percentage distribution of vehicle composition and consumption

Vehicle category	cars	motorcycles	buses	HGVs	LGVs	Total
Number of vehicles	73%	17%	1%	1%	8%	100%
Diesel consumption (tons/year)	25%	0%	36%	29%	10%	100%
Gasoline consumption tons/year)	88%	9%	0%	0%	3%	100%
Total consumption (pet/year)	46%	3%	24%	20%	8%	100%

Analyzing the consumption divided for each vehicle typology emerge that cars consume more than the 46% of the total, the goods vehicles about the 30%, the buses more than 20%, while the motorcycles consume about 3% of the pet/year.

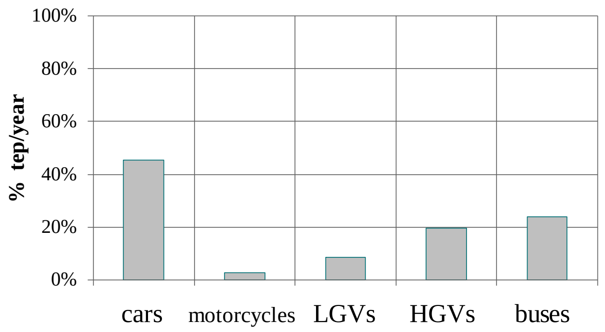

Fig.3 – Estimation results: percentage distribution of vehicle pet/year consumptions

With respect to the pollutant emissions results, both the greenhouse gases and fine particles PM10 were quantified. In estimation results were reported in Fig.4 and Fig.5 in term of percentage distribution among the vehicles types analysed. The emissions in Salerno were: 120 thousand tons/year of CO2, about 2 thousand tons/year of CO, more than 4 tons/year of NO2, more than 21 tons/year of methane and about 300 tons/year of VOC. Overall the environmental impact of transportation system in Salerno is 127 thousand tons/year of equivalent CO2. The impact of each vehicle typology estimated is:

- cars about 45% of the total CO2 equivalent;
- goods vehicles about 27% of the total CO2 equivalent;
- buses about 24% of the total CO2 equivalent;
- motorcycles about 4% of the total CO2 equivalent.

With respect to the PM10 emissions, in Salerno about 53 tons of PM10 are generated every year. The cars, as expected, are the vehicles which produces the highest percentage of this pollutant. Car emits about 12 tons/year of PM10 (about 23% of the total).

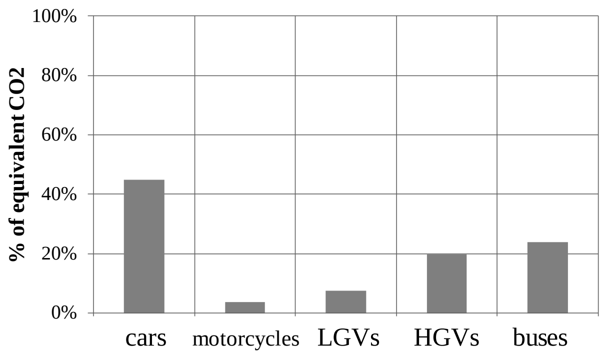

Fig.4 – Estimation results: percentage distribution of vehicle CO2/year emissions

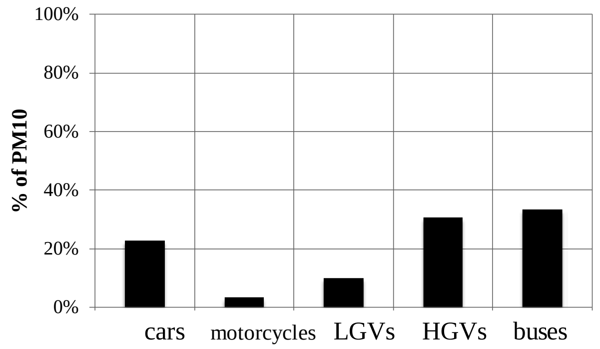

Fig.5 – Estimation results: percentage distribution of vehicle PM10/year emissions

2.1 A cost-benefit analysis regarding the renewing of the diesel bus fleet into electric vehicles

The environmental and energy implications deriving from renewing a percentage of the public transport diesel bus fleet into electric buses was also estimated. For this scenario, 10%, 20% and 30% percentage of updating bus fleet was tested, applying the estimation model described before.
In the following tables, estimation results are reported in terms of: equivalent CO2 emissions, PM10 emissions, total fuel consumption.

Tab.3 – Estimation results: total fuel consumption deriving from the updating a percentage of the diesel bus fleet into electric vehicles

% bus fleet updated	**0%**	**10%**	**20%**	**30%**
pet/year	42,79	41,763	40,736	39,709
Δ%	0%	-2.4%	-4.8%	-7.2%

Tab.4 – Estimation results: total fuel CO2 emissions deriving from the updating a percentage of the diesel bus fleet into electric vehicles

% bus fleet updated	**0%**	**10%**	**20%**	**30%**
tons/year	127,130	124,079	121,028	117,977
Δ%	0%	-2.4%	-4.8%	-7.2%

Tab.5 – Estimation results: total fuel PM10 emissions deriving from the updating a percentage of the diesel bus fleet into electric vehicles

% bus fleet updated	**0%**	**10%**	**20%**	**30%**
tons/year	53.1	51.3	49.6	47.8
Δ%	0%	-3.3%	-6.7%	-10.0%

As reported, the benefits produced in term of fuel consumption range between -2.4% (with a conversion rate of 10%) to -7.2% (with a conversion rate of 30%). A similar trend can be observed for CO2 equivalent emissions, while significant reductions can be obtained for PM10 emissions:

- -3.3% reduction of PM10 emissions, renewing the 10% of the diesel bus fleet into electric buses;
- -10.0% reduction of PM10 emissions, renewing the 30% of the diesel bus fleet into electric buses.

Starting from these results a cost-benefit analyses was performed verifying the economical convenience of these design scenario. The results were negative (less benefits than costs) because of the high acquisition cost for electric buses and the inefficiencies deriving from the low autonomy of the batteries. These conclusions suggest that this policy is not "eco-rational" for this case study.

2.2 A cost-benefit analysis regarding the renewing of the diesel bus fleet into diesel plug-in hybrid electric vehicles

A cost-benefit analysis was also performed regarding to an eco-rationality design scenario aimed at upgrading the Salerno public transport bus fleet into a diesel plug-in hybrid electric vehicle. To complete this scenario enlarging its environmental benefits, was designed to install, in each bus parking-area, a grid-connected photovoltaic system that yields energy to the grid during the day and recharge the bus through a plug-in system during the night. The best design of the photovoltaic system ensures a perfect balance between energy sold during the day and that absorbed during the night. This could significant reduce fuel consumption and emissions compared to the scheme with a simple diesel-hybrid upgrading of the bus fleet.

The costs and the benefits estimation for evaluating the economic returns of the investment was performed starting from through the unit values proposed in [11] (Tab.6). These are the result of the combination of a plug-in bus fleet with a photovoltaic system for charging the batteries.

Tab.6 – Cost-benefit unit values

diesel price (€/liter)	1.416
Acquisition cost for one diesel standard bus (€)	214,000
Average bus diesel consumption (km/liter)	2.5
photovoltaic system (€/kW)	5.229
Average annual energy produced by photovoltaic (kWh/kW)	1,300
Energy produced by the photovoltaic (kWh/ year)	221,964
Battery capacity (kWh)	32
Average number of daily battery recharges	1
Acquisition cost for one diesel Hybrid-plug bus (€)	373,000
Energy for recharge batteries (kWh/year)	221,964
Average hybrid plug-in bus Consumption (km/liter)	3.86
Number of bus updated	19
km/year per bus	69,5

The economic investment (Tab.7) was estimated considering:

- the cost of a standard diesel plug-in bus, the cost of standard photovoltaic panels and assuming:
- 8 hours/day operation time for the bus fleet;
- a full batteries re-charge at the end of each day.

In Tab. 7 results of three different design scenarios are reported:

1) Scenario 1: 10% of the buses operating within the municipality of Salerno were renewed in diesel plug-in hybrid electric vehicles and a photovoltaic system for charging the batteries was also implemented;
2) Scenario 2: 10% of the buses were renewed in diesel plug-in hybrid electric vehicles and each hybrid bus was equipped with two batteries (double autonomy) and a photovoltaic system for charging the batteries was also implemented;
3) Scenario 3: similar to the second, where it is expected a 25% reduction of the bus acquisition cost in the medium to long term.

Tab.7 – Estimation results: cost-benefit indicators

Scenario	1 battery /bus (Scen. 1)	2 batteries /bus (Scen. 2)	2 batteries/bus and -25% purchase costs of the hybrid bus (Scen. 3)
Total investment cost (millions of Euro)	3.950	4.830	2.820
Pay-back period (years)	12	10	6
net present value in 12 years (millions of Euro)	-0.780	0.008	2.020
net present value in 18 years (millions of Euro)	0.430	1.850	3.860

Starting from these results, environmental impacts deriving from the implementation of the proposed design scenario were estimated. Results are reported in the next tables. Regarding the Scenario 1, the investment cost is 3.9 million of Euro, the pay-back period is 12 years and a reduction in energy consumption and total emissions (Equivalent CO2 and PM10) was estimated equal to 1.8% and 1.8/2.4% respectively. For the Scenario 2 (two batteries/bus), was estimated an increase in investment costs (two batteries and the need of a more powerful photovoltaic system) against an increase in environmental benefits. In this scenario, the cost amounts in 4.8 million of Euro, the payback period is 10 years and was estimated a reduction in consumption and emissions of about 2.6% and 2.6/4.8% respectively. Finally, if we assume that in the next years the purchase and maintenance costs of bus hybrid vehicles will decrease up to the 25% (Scenario 3), the investment cost will be equal to 2.8 million of Euro with a pay-back period of 6 years (high investment cost-effectiveness).

4 Conclusions

Recently the idea of eco-rational planning has assumed a central role in urban sustainable transportation planning, that means financial effective, rational and effective for the transport system, sustainable for the people's health and for the environmental and acceptable by the stakeholders, and this was coherent with the development of new technology regarding the electric/hybrid bus fleets (e.g. [30]; [31]; [32]; [33]). Starting from the consideration in this research were estimated the environmental and energy implications deriving from the renewing a percentage of Salerno bus fleet into both electric and plug-in hybrid vehicles.

Results of the estimation show that updating (renewing) the 30% of the Salerno public transport bus fleet into electric vehicles will produce significant positive environmental impacts (fuel consumption and the equivalent CO2 emissions reduction equal to -7.2%, and PM10 reduction equal to -10.0%).

By contrast, from an economical point of view, the high acquisition cost for electric buses and the inefficiencies deriving from the low autonomy of the batteries suggest that this scenario is not "eco-rational" because of it is not economically convenient form a cost-benefit point of view.

In a second design scenario were estimated the environmental implications deriving from the renewing a percentage of the bus fleet into a diesel plug-in hybrid electric vehicle. Results of the estimation show comparable environmental impacts to those estimated using fully-electric buses, but in this case (for hybrid electric buses) was observed also an economical sustainability form a cost-benefit point of view, with an investment cost of 4.8 million of Euro and a payback period of about 10 years.

One of the research perspectives will be to apply the proposed methodology to estimate the environmental impacts and the investment costs deriving from the installation of an automotive after-market mild-solar-hybridization kit [34] and/or for a carsharing services [35].

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