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Design and evaluation of electric solutions for public transport

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Abstract

This study deals with the design and the evaluation of technological solutions for the electrification of public transport in urban areas. A Decision Support System (DSS) developed by ENEA[†] within the Research program on Electric System (RSE) has been adopted in order to verify the technical feasibility of several electric architectures of single bus lines and compare the investment and management costs, as well as the external costs due to vehicle emissions and noises, of the feasible solutions with respect to the conventional alternatives (Compressed Natural Gas, CNG, and diesel).
The DSS has been applied to several bus lines located in the south-west area of the city of Rome, Italy, and covering different types of service: peripheral lines, main lines connecting suburbs with the city center and secondary lines going to the main metro stations. Input data for the DSS derived both by simulation and by open database available from the public transport operator in Rome (ATAC). Results show that a suitable electric architecture can be found for each of these lines with lower or comparable total costs with respect to the traditional alternatives. Finally, a sensitivity analysis has been performed considering several scenarios in terms of discount rate of recharge stations and batteries, battery's duration, price of conventional fuels.

Keywords: Battery Electric Buses; e-buses; opportunity (on-route) charging; decision support system

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1. Introduction

Road vehicular emissions in our cities are reaching critical levels. An increase in the use of alternative fuels (biodiesel, gas, or electricity) and latest-generation bus engines represent a possible strategy in the public transport sector to obtain significant emissions savings.

Battery Electric Buses (BEBs) are emerging types of "clean" buses and even more cities in the world are choosing this technology to deal with poor air quality and noise (Seredynski and Viti, 2016). Since starting operations in 2012, Nottingham City Council's fleet of 45 electric buses have reduced CO2 emissions by more than 1,000 tons at a third of the running cost. In Milton Keynes Arriva successfully operates UK's first all-electric route, which includes the first UK application of inductive charging. It is generating huge savings in both fuel costs and carbon emissions compared with diesel vehicles (Haigh, 2016).

The energy storage capability is one of the most important features when dealing with BEBs and two categories of BEBs can be defined as a function of the battery characteristics: 1) first category BEBs, adopting medium capacity batteries (typically 20-60 kWh, CIVITAS Tech. Rep. 2016), charged at end stations of routes for approximately 4 to 6 minutes. This charging system is usually known as opportunity (on-route) charging; 2) second category BEBs adopt large battery packs—typically 200-350 kWh (CIVITAS Tech. Rep. 2016)—that are charged at night in bus depots.

Several new BEBs system deployments with on-route charging started to emerge. In the United States (San Gabriel region, California) Proterra/Eaton BEV system with 88 kWh battery is charged on-route via 500-kW fast charge with an average charge duration of 5 minutes (Prohaska *et al.*, 2016). In the TOSA system deployed in Switzerland (ABB/HESS), a BEB with battery capacity of 38 kWh is charged in route terminals for 4 to 5 minutes with 200 kW (Patey *et al.*, 2016). Additionally, 600kW boost are performed at bus stops every 1 to 1.5 kilometers for 15 seconds. In Luxembourg (ABB/Volvo), a plug-in hybrid BEB is charged at terminus stations for 6 minutes with a 150 kW boost. In Charleroi and Namur (Belgium), the public transport operator TEC Group has ordered 12 opportunity charging stations and 90 electric hybrid buses (ABB/Volvo): delivery and installation will get under way in autumn 2017.

In general, charging infrastructure results in strong dependency between infrastructure planning and bus operations (Rogge *et al.*, 2015). The White Paper on "Best practices regarding electric vehicles" reports that only with proper planning, transportation electrification can result in "*more efficient and less costly operation of the grid, provide ancillary services, lower electricity prices for ratepayers, and facilitate greater integration of renewable energy resources*". Therefore, existing research deals on BEB system design from the perspective of locations of battery charging stations (Fusco *et al.*, 2012, Pternea *et al.*, 2015). Simultaneously, energy efficiency aspects are also addressed from the perspective of engine energy management strategies (Peng *et al.*, 2017), battery management (Cai *et al.*, 2016) and regenerative breaking technologies (Li *et al.*, 2016).

This study deals with the design and the evaluation of technological solutions for the electrification of public transport in urban areas. A Decision Support System (DSS) developed by the Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA) within the Research program on Electric System has been adopted in order to verify the technical feasibility of several proposed architectures based on the most recent BEB's technologies. Then, the DSS compares the investment and management costs, as well as the external costs due to vehicle emissions and noises, of the feasible architectures respect to the standard fuel alternatives (Compressed Natural Gas - CNG, and diesel).

The paper contains four sections including this introduction: Section 2 deals with a description of the DSS in terms of electrical architectures considered, technical feasibility checks implemented and internal and external costs evaluation. Section 3 presents the application of the DSS on a set of five bus lines in Rome (Italy). Moreover, a sensitivity analysis has been conducted modifying the discount rate of recharge stations and batteries, battery's duration and price of conventional fuels. Conclusions follow in Section 4.

2. The Decision Support System

The electrification of the urban public transport with BEBs requires an accurate verification of the technical and economic feasibility. For this purpose, in the latest year (2015-2016) of the Research Programme on the National

Electric System, funded by the Italian Ministry for the Economy, ENEA developed a tool supporting the choices of public transport Operators in this kind of projects, named Better Electric Solutions for Public Transport (BEST).

BEST examines bus lines one by one, assuming for each of them a specific vehicle size, namely the more frequent among the ones possibly used for the actual operation; it considers three electrification solutions, which correspond to as many operational models: i) Architecture A: overnight slow charge at the depot (charging time of some hours). The vehicles are fitted with a big capacity batteries (some hundreds of kWhs); ii) Architecture B: opportunity charge at the terminals (charging time of few minutes), plus the overnight charge at the depot. Vehicles are provided with smaller batteries (some tens of kWhs); iii) Architecture C: flash charge at the stops (charging time of few seconds), opportunity charge at the terminals and slow charge at the depot. Vehicles are equipped with small capacity electric storage (some units of kWhs).

A specific kind of on-board storage is assigned to each architecture, lithium-ion batteries for the architecture A and B, while super capacitors are provided for the C solution for the main on-board electric storage (and lithium-ion for the back-up battery ensuring the operation of the bus line in case of failure of some charging stations). Super capacitors are extremely durable and very suitable for high power and ultrafast recharge but, on the other hand, are heavier, larger and significantly more expensive per kWh, when compared to conventional batteries; however, in case of frequent charges, the overall capacity of the storage, and consequently dimensions, weight and costs, can be adequately reduced. In addition to the three electric solutions, also conventional alternatives are considered for the economic and environmental comparison, namely the alimentation with diesel and CNG.

BEST is composed of four calculation modules allowing, respectively: 1) to estimate energy consumption and gaseous emissions for all the different technological alternatives; 2) to verify the technical feasibility of the three electric architectures and to size the on-board storage and the related power supply system; 3) to compare the feasible solutions, both electric or conventional, from an economic point of view, using a function of investment and operating costs; 4) lastly, to estimate the social external costs generated by pollutant emissions and vehicular noise.

The latest three modules are integrated into a unique software program while the first one was developed separately and interacts with the others by means of a common database. As for input data, BEST utilises the ENEA technological expertise on electric vehicles and recharge stations; moreover, open data in GTFS format are gathered directly from the web to reconstruct actual bus line operation during a year; in practice, some typical days are examined for each seasonal and weekly period. Costs items are derived from commercial information and specialised literature. A number of case studies have been analysed in order to verify BEST functioning and likelihood of its results. So far, BEST represents a peculiarity into the Italian offer of such kind of tool, even if some similar models have been carried out all over the world. Many of them are focused on the optimal scheduling of electric bus fleets (Reuer et al, 2015; Paul et al, 2014) or utilize a simulation approach to the problem of electrification (de Filippo et al. , 2014); also the optimal design of electric Public Transport networks has been faced (Fusco et al, 2013; Kunith et al. 2016) but not the on-board storage and recharge stations dimensioning and the economic evaluation of single bus lines based on open data.

2.1. Consumption and emissions estimation

For the calculation of noxious emissions and energy consumptions, BEST applies ECOTRIP (Emission and Consumption Calculation Software Based on Trip Data), a model developed by ENEA able to provide geo-referenced estimates of the pollutant emissions, climate-change emissions and fuel consumptions (Valenti et al., 2017). In particular, emissions and consumptions are estimated for each single stop-to-stop link of each single bus ride. The calculation procedure requires both bus load factor and mean speed, as well as road stretch's mean slope. It applies, for the conventional vehicles, the speed-dependent hot emission and energy consumption factors described in the EMEP/EEA emission inventory guidebook (Ntziachristos et al., 2016), while for the electric buses it makes use of specific consumption functions carried out by the University of L'Aquila through simulation of suitable driving cycle, always within the same RSE Programme.

2.2. Technical feasibility analysis

With a preliminary analysis, BEST immediately discards the solutions technically unfeasible, for example due to obstacles to the installations of recharge stations or to inappropriate energy needs, according to different recharge architectures. Subsequently, the procedure provides for the dimensioning of the on-board storage and the recharge stations, using the results of the energy consumption calculation and considering the power supply opportunities for each architecture. Architecture A is sized on the daily consumption (typically more than 100 kWh), i.e. the average consumption of a single vehicle for the most critical day of the year, Architecture B is sized on the highest consumption for a single race (typically some tens of kWh) and the Architecture C is sized on the highest value of consumption between two intermediate charging stations (typically some kWh). The three architectures are simultaneously verified and sized. Project assumptions are made on recharge duration in each situation: 6 hours at depots, 8÷10 minutes at terminals, depending on the size of vehicle, 15÷20 seconds at intermediate stops.

Outputs of this analysis are the electric vehicles storage capacity, in terms of kWh, and the number and the power of the recharge stations, in terms of kW. For the storage capacity, only upper bounds are taken into account, according to vehicle size and storage type, while for the recharge power, a discrete number of possible values are considered for each kind of installation, considering actual commercial offer. The number of recharge stations at terminals are determined considering possible overlapping of recharge times during the operation day, for a maximum of two stations per line, while at stops, thinking of the short recharge time, overlapping are excluded, apart from possible operation anomalies.

2.3. Internal and external costs evaluation

Once the electrical architectures are sized, the economic model evaluates the most convenient solution, which will be compared, in a second phase, to the conventional alternatives. This economic assessment is carried out with Cost-Benefits Analysis techniques. Such an analysis helps operators to measure the profitability of their investments and to verify the compliance with spending constraints.

The model estimates the Net Present Value (NPV) of each option for fixed time period and discount rate, considering only those items that make difference among the various technological alternatives, i.e. investments for vehicles and recharge stations and operational costs. The NPV results always negative, so that the preferable alternative will be the one with the lowest negative NPV. The costs considered in the model are: 1) initial investments for vehicles, on-board energy storage and charging stations; 2) investments for possible replacement of the same three factors during the analysis period; 3) the energy costs for vehicles operation, corresponding with the expenditures for fuel in case of conventional vehicles and with the electricity bill in case of BEBs; in this case not only the energy totally absorbed from the power network is considered but also the level of voltage needed to charge, the nominal power required and the number of withdrawal points; 4) the maintenance costs of vehicles and charging infrastructures; 5) the residual values of the production factors at the moment of their replacement at the end of life or at the end of the analysis period.

Typically, Architecture A requires high investments for on-board storage and low costs for recharge installation, despite Architecture B and C; as for operation, energy costs are higher in the Architecture A, due to heavier electric storage than B and C.

The economic analysis requires several preliminary elaborations for the estimation of some input variables, in addition to the results of the feasibility analysis and specifically: the annual mileage of vehicles, invariant for all the technological alternatives; the annual energy consumption according to technological vehicles characteristics and load factor daily, weekly and seasonal variations; the number of buses needed to effect the transport service, as a function of the time possibly required for opportunity electric recharge; the power required taking account of the likelihood that more vehicles can be simultaneously recharged.

The economic analysis is integrated with the computation of the external costs generated from gaseous and noise emissions for each technology solution; the model does not consider the environmental impact of exhausted on-board storage. The model applies the specific damage values reported in the European Handbook on external costs of transport (Ricardo-AEA, 2014). For the harmful emissions with mainly local effects, the model considers only the Processing-to-Wheel (PTW) phase, due to a marginal involvement of the Italian territory in the Well-to-Processing phase. For the Particulate Matter (PM) and noise as well, different unit costs related to population density of the buses circulation area are used, as indicated in the Handbook. For the CO2 emissions, with global impact, the model considers the whole cycle Well to Wheel.

3. Application of the DSS in a real case of study

Five bus lines located in the south-west area of the city of Rome, Italy, have been selected in order to test the reliability and the sensitivity of BEST. The economic analysis has been carried out for a period of twelve years and a 5% discount rate. The selected lines cover different types of service, thus being a representative sample of the entire population: from peripheral lines to main lines connecting suburbs with the city centre and secondary lines going to the main metro stations.

The dataset published in the open data format by the Mobility Agency of Rome, includes the lines, the routes, the timetables, that characterized the public transport service. The dataset was also enriched with information on the type of bus used, on passengers demand data, on the slopes of each individual section for a more accurate estimate of energy consumption and polluting emissions.

To proceed with the computation of the consumptions and the pollutant emissions, passenger demand data and, specifically load factors of the bus lines are required. Actually, the total weight of vehicles can significantly vary in accordance with the number of the passenger on-board and this affects energy consumption and tail-pipe emissions. Since information on load factors is not available from the open data, a simulation model has been applied to obtain them.

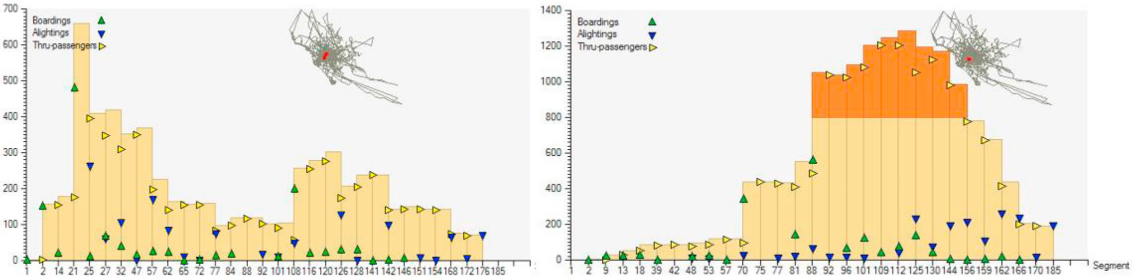

Fig. 1. Loading diagram for both the direction of the bus line number 170 during the morning peak hour.

Starting from the current scenario adopted by the Mobility Agency of Rome for the morning peak hour (8:00-9:00) and based on a multiclass assignment procedure, other three scenarios have been created and simulated: i) the morning off-peak (11:00-12:00); ii) the afternoon peak (16:00-17:00); and the afternoon off-peak scenario (19:00-20:00). Origin-Destination (OD) matrices, related to both the private and public demand, have been obtained reducing the respective morning peak hour matrices in accordance with the distribution of the private vehicles daily demand provided by the Mobility Agency. Then, for the afternoon scenarios, OD matrices have been transposed. Headways of public transit lines have been reduced for the off-peak scenarios accordingly to the current service in Rome. The resulting load factors for each bus line and segment (e.g. Fig.1 for bus line number 170) have been extended to the not simulated hours of the weekday, joining each time interval to a specific simulated scenario and scaling the simulation results as a function of private vehicles daily demand distribution. In such hypothesis, it is assumed the same temporal trend for both the private and the public transport daily demand.

Load factors for the nighttime have been obtained adopting a linear trend of the values between the 11:00 pm and the 4:00 am. For the summer weekdays, load factors previously computed have been reduced of -30% due to the lack of the school population and to the increased adoption of the car for that season. Finally, for the weekend days a reduction of -70% of the load factors has been hypothesized for both the winter and the summer season.

4. Results

The following results have been obtained for the five case study, in terms of internal and external costs (Fig. 2 and 3). Only the Architecture B is feasible in all cases, while the other two alternatives cannot be always carried out, due to energy consumption over the limits allowed by the on-board storage characteristics. Even when A and C are feasible, they are usually outperformed by B in terms of internal costs.

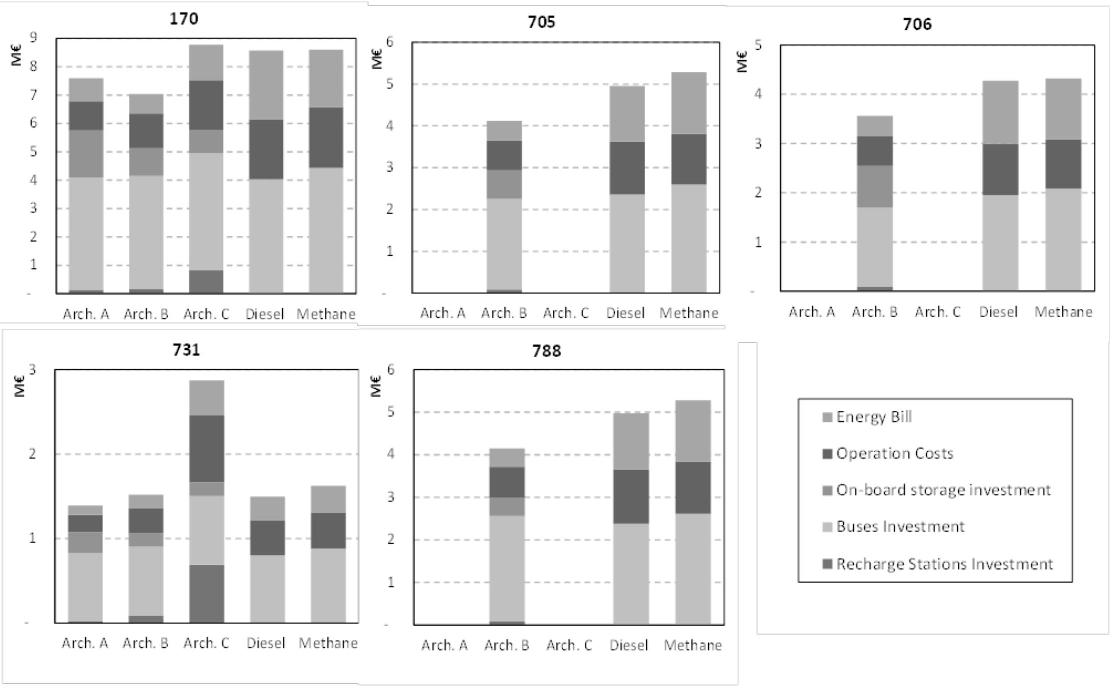

Fig. 2. Internal costs for the various technological alternatives.

The costs making the difference between the three architectures relate to the charging system and to the on-board energy storage. Globally, these two items generally represent the second expenditure of a BEB line (about 20% as a mode), following the investment for fleet purchasing (around 50%). Of course, investments for recharge are prevalent for Architecture C, many times higher than for Architecture A and B. Instead, the investment for the on-board energy storage is higher for Architecture A (some tens of percent higher than B and two times higher than C).

The impact of the electric bill is 10-20% of the total internal costs. The costs for the connection to the grid and committed power are much higher for Architecture C than A and B, since many high power withdrawals for the super-fast charge at stops are needed. Instead, the cost of the energy consumption is higher for Architecture A (double than B and C), with an impact on the energy costs of 80%, due to the weight of the on-board energy storage. Maintenance is more onerous for B and, above all, for C, due to the recharge installation needs.

For all the analyzed lines, total internal costs of the selected electric solution are always lower with respect to CNG and diesel, although not dramatically. The main advantages of the electrification are in the energy and maintenance costs which, for the Architecture B specially, overcome the disadvantages of higher investment for recharge and electric storage.

As for the external costs of noxious emissions and noise, electric vehicles perform even better, with level of costs many times lower in comparison with diesel and methane. No emissions and lower noise during vehicles operation (Tank-to-Wheel phase) make the difference, although the pollution during the up-stream phase, linked to the electricity production, is higher. Costs of noise and Production-To-Tank emissions (Well-to-Tank in case of CO2) for electric buses are equally subdivided. Instead, local pollution during vehicle operation represents the main externality of diesel and methane, even if noise is not negligible, mainly for diesel buses; on the contrary, emissions in the up-stream phase produce marginal external costs, lower than the electric alternative.

The CNG is the fuel alternative with higher externalities linked to noxious emissions, since NOx and HC (namely CH4) emissions are respectively 1.5 times higher and 20 times higher in CNG than diesel. It should be noted, however, that these data refer to EEV's and not to EURO VI, which are on the market nowadays and perform better than older EEV.

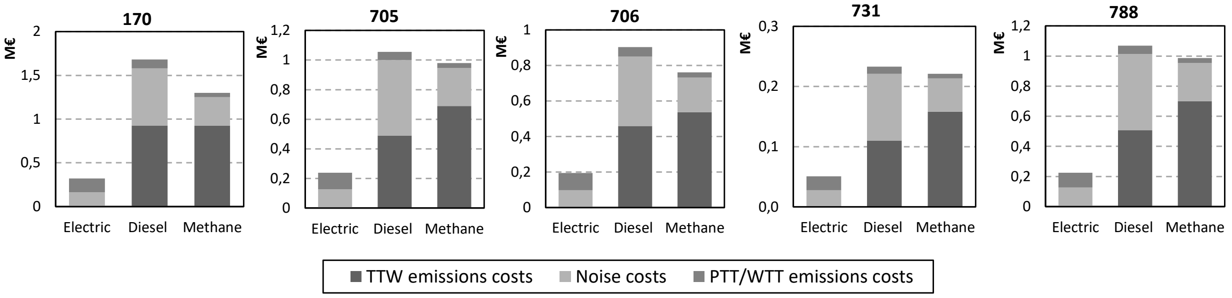

Fig. 3. External costs for the various technological alternatives.

In the following sections, a sample sensitivity analysis for one bus line (#170) has been reported, finalized to verify the robustness of the technological ranking. First, the investments for Architecture C have been reduced, doubling the discount applied on recharge stations and super-caps; then, it was assumed a shorter lithium-ion batteries duration for architecture B; last, a lower price of conventional fuels was considered.

4.1. Sensitivity analysis

BEST considers the possibility to apply discounts on several items, i.e. vehicles, recharge stations, electric storage. In the reference scenario, discount on super-caps and flash-charge stations were maintained low (-10%), assuming that the market is not ready for this technological solution yet. For the sensitivity analysis, a new scenario with higher discounts on both high-power recharge stations and super-caps has been investigated, doubling the discounts respect to the reference scenario. The objective of this analysis was to verify if, in a medium-term horizon, the opportunity recharge at stops can be competitive with respect to the recharge at terminals or depots. Despite a reduction of the overall costs of the Architecture C (-5%), it remains the most expensive solution for the electrification of line 170.

So far, the effective duration of lithium-ion batteries submitted to frequent fast recharges, as in the case of the Architecture B, is not clearly determined. In the reference scenario, considering that the Architecture B battery is oversized to guarantee the needed power, so that the Depth-Of-Discharge (DOD) is not higher than 40%, the number of possible charge-discharge cycles has been doubled respect to the value related to deeper discharges (80%), as they happens for the Architecture A. As it is assumed that the lithium-ion battery duration for A is 2.000 charge-discharge cycles, the hypothetical duration for B results to be 4.000 cycles; it must be considered, however, that in this second case, a higher number of charge-discharge cycles occurs per operation day so that, in practice, the duration in terms of time is much shorter for B than for A. In order to consider that the high electric current applied during fast recharges could reduce the battery durability (even if a correct operation practice should minimize this negative impact), in a pessimistic scenario, the possible charge-discharge cycles for the Architecture B have been reduced to 3.000. Despite to this penalization, Architecture B still remains the less expensive for the line 170.

A big uncertainty of conventional vs electric comparison is the price of diesel, due to both fluctuations of oil prices and changes in excises. In the reference scenario, the diesel price was already quite low for the Italian context (about 0.94 €/l), having considered the tax breaks applied for PT services in our Country. A further reduction of

10% has been assumed in a more optimistic scenario, to verify if also in this case the electric solution is cheaper that diesel; the sensitivity analysis confirms this result for the case study.

5. Conclusions

This study reports the results of the application of a Decision Support System (DSS) named Better Electric Solutions for public Transport (BEST) developed by ENEA within the Research program on Electric System and founded by the Italian Ministry of the Environment. BEST deals with the design and the evaluation of technological solutions for the electrification of public transport in urban areas. Specifically, it works analyzing several proposed architectures, based on the most recent battery electric buses technologies, in terms of their technical feasibility, as well as in terms of investment and management costs. Moreover, it permits to compare the best resulting electric alternative with standard fuel alternatives, as CNG and diesel, both in terms of internal costs and external costs due to vehicle emissions and noises. The application of BEST to several bus lines in Rome has shown, in most cases, the convenience of the electrical architecture based on combining the overnight slow charge at the depot and the opportunity charge at the terminals. Moreover, results of BEST confirm that operating costs of a full electric vehicle are less than of its conventional counterparts and the electrification would seem to be, in the medium to long term, more cost effective than conventional technologies.

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