Impact of Critical Variables on Economic Viability of Converted Diesel City Bus into Electric Bus

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Abstract. Through the European Strategy for low-emission MOBILITY of 2016, the European Commission is working to strengthen the economy by promoting sustainable urban mobility and increased use of clean and energy efficient vehicles and looking into how to accelerate this process. Cities are crucial for the delivery of this strategy, and electrification of buses is a step towards reducing the fossil fuel dependency of the transportation sector as well as creation of a healthier urban environment.

At the same time electric buses are still a challenge for public transport operators due to high acquisition costs of a new vehicle and lack of charging infrastructure. Therefore, conversion of diesel city bus into electric bus is one of the alternatives considered. Economic viability of converted diesel bus into electric bus can be parameterized using an economic model that allows to estimate an impact of critical variables on the total cost of ownership.

In this paper, a specific case of operating converted diesel bus into electric bus in a city of Latvia is analyzed. With the help of economic model, critical variables are determined as well as their switching values, which make the use of converted diesel engine bus into an electric vehicle economically viable. It can be used to support decision-making process of public transport stakeholders in the context of the deployment of environmentally friendly public transport.

Keywords: Low-emission · Electric bus · Converted diesel bus
Economic analysis · Total cost of ownership · Sensitivity analysis

1 Introduction

A European Strategy for Low-Emission Mobility [1] states that Europe needs to accelerate the transition towards low- and zero-emission vehicles like some plug-in hybrids, full electric cars and fuel cell (i.e. hydrogen-powered) vehicles. Transition to a low-carbon economy is supported in all EU countries, including Latvia. Through the Strategy, the European Commission is working to strengthen the economy by promoting sustainable urban mobility and increased use of clean and energy efficient vehicles, and looking into how to accelerate this process. One of the EU transport sector goals stated in the White Book [2] is to reduce CO_2 emissions by 60% until 2030. Transport, in particular urban transport, uses a great share of energy resources.

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Urban public transport (PT) is in the process of transformation driven by technological developments and demand for environmentally friendly, energy-efficient, cost-effective, and smart mobility. Cities are crucial for the delivery of European Strategy for low-emission, and electrification of buses is a step towards reducing the fossil fuel dependency of the transportation sector as well as creation of a healthier urban environment and reducing the impact on climate change.

At the same time electric buses are still a challenge for PT operators due to high acquisition costs of a new vehicle and lack of charging infrastructure. The development of local economy along with the technological opportunities are important factors to be considered in the decision-making regarding the use of electric buses in a city. A new electric bus is a costly investment for a company providing PT services in small and mid-size cities with a population of 20 000 up to 200 000 (according to the definition of a medium-sized town in [3]). Therefore, solutions have been sought to look for less expensive alternatives that meet the goals of a low-carbon economy and sustainable urban mobility.

Innovative technologies increasingly oriented towards electrification of vehicle propulsion systems are expected to lead to: (i) a reduction of harmful emissions, (ii) an increased efficiency of vehicles, (iii) improved performances, (iv) a reduction of fuel consumption, (v) a reduction of noise, and (vi) potentially lower maintenance costs [4]. Conversion of a used diesel bus into an electric bus allows to substitute electricity for diesel with minimal changes to existing fleet.

This study focuses on mid-size city diesel buses that are used in the urban environment. As a bus ages, operating and maintaining (O&M) costs tend to increase. At this point the strategic decision has to be made – to renew the fleet or to modernize the existing fleet. The research aim is to assess economic viability of the proposed solution: converting a diesel city bus into the environmentally friendly electric bus.

The structure of the paper is the following: the methodology of estimation an impact of critical variables on the total cost of ownership is described in Sect. 2; in Sect. 3, the results and discussion of a specific case of operating converted diesel bus into electric bus in a city of Latvia are presented; and the last part offers conclusions.

2 Methodology

Total Cost of Ownership (TCO) model is utilized in this research to determine economic viability of a diesel bus conversion into an electric bus, and sensitivity analysis is used to assess the impact of critical variables on the TCO. Life cycle costs for buses with different types of engine (diesel and electric) are compared to evaluate cost-effectiveness of the conversion process.

The analysis focuses on the mid-size buses up to 12 m long with the capacity of 80 passengers used in the urban environment, which is affecting the operational phase related impacts, as well as investment costs. The average annual distance is assumed to be 60 000 km. Diesel bus used for PT services in the city has a lifecycle of 10 years. There are major costs cycles that repeat throughout the bus life and the cost peak is reached at roughly 6 to 7 years [5]. Thus it is assumed to be optimal timing to convert the diesel bus into the electric bus.

2.1 Total Cost of Ownership Model

TCO analysis is a method to assess life-cycle costs that include all costs of purchasing, operating, and maintaining the vehicle. The economic analysis model is prepared with the objective function to calculate TCO for the diesel bus (DB) and the converted electric bus (EB). The comparison of the results allows to assess economic viability of the DB replacement with the EB for PT services in the urban environment.

In case of EB, availability of charging infrastructure has to be considered. If the infrastructure is not in place for charging electric buses, then the investment costs of charging infrastructure as well as costs of grid connection are also included in the TCO calculation.

TCO include the vehicle costs, the charging infrastructure costs, and external costs:

$$TCO = CInv\,(bus) + CInv\,(charger) + CInv\,(grid) + C(O\&M) + I * C(ext) \quad (1)$$

where CInv (bus) - investment costs of a bus; CInv (charger) - investment costs of a charger; *CInv (grid)* - investment costs of a grid connection; *C(O&M)* - operating and maintenance costs for the vehicle and the charger; *C(ext)* - external (environmental) costs; and indicator *I,* that equal to 1 for DB, and to 0 for EB.

External (environmental) costs *C(ext)* are considered in this analysis because these costs relate to the damage of human health and ecosystems associated with air pollution and emissions of greenhouse gases (GHG), and are calculated as follows:

$$C(ext) = C(CO_2) + C(NO_X) + C(PM) \quad (2)$$

where $C(CO_2)$ - costs of CO_2 emissions; $C(NO_X)$ - costs of air pollution (Nitrogen oxides (NO_X)); and *C(PM)* - cost of particulates (PM).

The damage of human health and ecosystems are mainly caused by the vehicles with internal combustion engines. Electric vehicles do not create GHG emissions but they may increase CO_2 emissions generated in electricity production. Since the main energy source (70%) is water power in Latvia (the rest being renewable energy 3.5% and fossil fuel 26.5%, out of which coal is 2% only), the CO_2 emissions generated in electricity production are not included in the analysis [6].

Costs of CO_2 emissions are calculated for the DB using the following formula:

$$CO_2 = CO_2\,\text{emissions}\ (\text{g/km}) * \text{cost}\ (\text{EUR/g}\ CO_2) * \text{annual mileage}\ (\text{km}) \quad (3)$$

$C(NO_X)$ - costs of air pollution and *C(PM)* are calculated on the same basis.

For the comparison purposes TCO is expressed in Equivalent Annual Cost (EAC), which includes cost of owning, operating and maintaining an asset. The present value of capital investment costs is expressed in equal annual payments using Capital Recovery Factor, at a discount rate of 4% [7]. EAC shows the net present value of an investment through annuity factors and therefore allows to do a comparison relative to time. The total cost of ownership is expressed as cost per kilometer (€/km), and is calculated dividing EAC by the number of annual operation kilometres. All prices are given net of VAT.

2.2 TCO Model Assumptions and Parameterization

Economic analysis includes both mathematical and expert estimations regarding model development, e.g. some cost items are included on constant bases whereas others require expert evaluation based on specific location, situation, and mostly on availability of necessary infrastructure for the use of EB.

Variables used in the TCO model and their values are given in the Table 1. The variables are identified as the main indicators of cost-effectiveness, which is the measure of outcome.

Table 1. TCO model variables and their values.

Asset	Variable	Value (DB)	Value (EB)
Vehicle	Investment cost	200 000 €	196 700 €
	Useful life	10 years	7 years
	Energy consumption	10.4 MJ/km (29 l/100 km)	1.2 kWh/km
	Energy price	1.00 €/liter	0.11215 €/kWh
	Urea, oil	0.011 €/km	n/a
	Maintenance and repair	0.15 €/km	0.10 €/km
	Transport operating tax	0.002 €/km	n/a
Charging infrastructure	Investment cost of charging infrastructure	n/a	150 000 €
	Charging infrastructure maintenance	n/a	1 000 €/year
Grid connection	Investment cost of grid connection	n/a	30 000 €
	Transmission power maintenance	n/a	19.56 €/kW/year
	Electricity transmission tariff	n/a	0.02129 €/kWh

The price of the converted EB is estimated taking the remaining value of the 7-year old diesel bus, subtracting the re-sell value of diesel engine and transmission system, and adding the cost of battery, electric drive and other supplementary materials, as well as labor costs. Battery is the most expensive component of the electric bus. According to the historical trend of battery price, the cost of batteries is expected to decrease in the future. Department of Energy of the United States predicts that with new material chemistries and lower-cost manufacturing, cost parity with internal combustion engines could be reached in the next ten years [8].

It is assumed that mid-size urban PT buses travel around 200 km a day without returning to the depot. Fast charging infrastructure, also known as opportunity charging, with pantograph is selected in this analysis because it allows to use comparatively small batteries which can be easily integrated into the vehicle [9]. Smaller battery means less initial investment cost, less weight, and more room inside the bus for passengers. Charging infrastructure includes the following elements:

- a static conductive fast charging station;
- pantograph coming down from an overhead charging mast;
- contact rails to be placed on the roof of the vehicle;
- Wi-Fi protocol for communication between vehicle and charging mast.

The charging infrastructure can be used by several buses on the line therefore investment costs are calculated proportionally to the number of buses using the charger. In the analyzed scenario, the quick charger can be used up to 6 vehicles per hour assuming charging time 9 min per vehicle. The realistic scenario of 5 vehicles is used in calculations. Fast charging infrastructure requires very little maintenance, just periodic inspection with estimated annual costs of 1000 EUR.

It is assumed that the charging infrastructure is owned by the bus company therefore the grid connection costs have to be considered as well, if a new connection to the power grid is required. With the estimated charger power of 150–300 kW, a connection to the low-voltage 6–20 kV line is sufficient. In this case, annual energy transmission service costs have to be considered for the owner of the charging infrastructure.

The energy consumption of electric bus is estimated at 1.2 kWh/km in the conditions typical for the average medium-sized city in a relatively flat area using the mathematical model which was created within the study to evaluate the effectiveness of the electric bus. The maintenance costs of electric drive system are expected to be 30% less compared to combustion power transmission system because it requires less frequent service maintenance. Electric drivetrains have less subsystems - no transmission, no oil tank, no catalytic converter. Also, electric vehicles can be exempt from transport operating tax (as it is in Latvia).

Refueling infrastructure for DB is not included in the TCO calculations assuming that this infrastructure has been in place already for 7 years and does not require additional investments for the bus operator.

2.3 Sensitivity Analysis

Sensitivity analysis method is used to identify the critical variables and to assess their impact on the model results. It allows establishing the financial sustainability level of the project given by the potential changes of the influence factors and serves, at the same time, to measure the project risk in order to justify decisions [10].

Let consider the ***critical variables*** as variables whose variations (positive or negative) have the largest impact on the TCO. The analysis is carried out by varying one variable at a time and determining the effect of that change on the TCO model results. In this research, variables are to be considered ‘critical’ for which a variation of $\pm 1\%$ of the value adopted in the base case gives rise to a variation of more than 0.2% in the value of the TCO results. The cost-effectiveness of the conversion process depends heavily on those variables whose value changing up to 20% results in a disadvantage of the use of EB. It is assumed that the tested variables are independent.

On the next step ***switching values*** are calculated. It is the value that the analysed variable would have to take in order for the TCO of the EB become equal to the TCO of DB, or more generally, for the outcome of the bus conversion project to fall below the minimum level of acceptability from the economic point of view. The use of switching values in sensitivity analysis allows making some judgements on the risk of the project and the opportunity of undertaking risk preventing actions [4].

3 Results and Discussion

The main results of TCO analysis are shown in Fig. 1. The calculated TCO of the diesel bus is 1.44 €/km, including environmental costs 0.05 €/km. It should be noted that in some studies, in which the comparison of the buses is performed [11], labour costs, insurance costs and vehicle tax are not included in the TCO calculation, whereas in this study all costs related to owning, operation and maintenance of the bus are considered in the TCO. For the diesel bus, investment costs form 28% of total TCO. The price of the 7-years old diesel bus converted into the electric bus is similar to the new diesel bus, but because of shorter remaining lifetime (7 years), the investment costs comprise a bigger share in the TCO (39%). The total TCO of the electric bus is 1.40 €/km, which include costs of charging infrastructure (0.07 €/km) and grid connection costs (0.03 €/km).

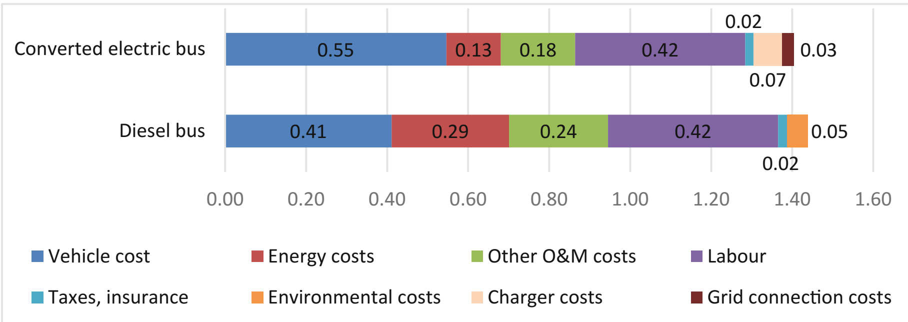

Fig. 1. TCO analysis results of diesel city buses in comparison with converted diesel bus into electric bus (EUR).

If the comparison is made for bus costs only (excluding infrastructure and external costs), the total TCO of the EB is 6% less than that of the DB. Significant part of converted bus price is the cost of the battery (36%). Battery is the most expensive component of an electric vehicle, and therefore is tested in the sensitivity analysis.

Significant benefit of DB conversion into EB is the reduction of energy costs. In the first case, the fuel costs are 20% of TCO, whereas after the conversion, the energy costs reduce 2.2 times due to significant reduction in energy consumption. O&M costs also decrease for the electric vehicle (by 20% in total) because there is no need for liquids such as engine oil and urea, and less frequent service maintenance required.

Based on the TCO results, investment costs and O&M costs are found to be critical for the sensitivity of economic justification (see Table 2). An increase in energy consumption or in electricity tariff is not a threat to the economic benefit of a bus conversion. It may be assumed that due to technological development, the price of the battery has a decreasing trend over time.

Table 2. Elasticity of equivalent annual TCO.

Variables	DB TCO change	EB TCO change
Vehicle parameters		
Investment costs	0.29%	0.39%
O&M costs	0.68%	0.54%
Cost of electricity	-	0.10%
Battery cost	-	0.17%
Energy consumption	0.20%	0.10%
Charging infrastructure parameters		
Charger infrastructure costs	-	0.04%
Number of buses using charger	-	0.07%

Using the TCO model, the switching values of critical variables are determined in order to have the conversion of the DB into the EB economically viable (see Table 3). The switching values of critical variables are those values at which the equivalent economic annual costs of DB and EB become equal. If the cost of conversion of DB into EB will be 6% higher than estimated in this study then the conversion will not be economically viable. If the total O&M costs of DB will reduce by 3% or O&M costs of

Table 3. Switching values of variables.

Variables	Benchmark value	Switching value	
		DB	EB
Vehicle parameters			
Investment costs (DB)	200 000 EUR	−8%	-
Investment costs (EB)	196 700 EUR	-	6%
O&M costs per year (DB)	58 578 EUR	−3%	-
O&M costs per year (EB)	45 475 EUR	-	4%
Cost of electricity	0.11215 EUR/kWh	-	25%
Battery cost	70 000 EUR	-	14%
Energy consumption (EB)	1.2 kWh/km	-	25%
Energy consumption (DB)	29 l/100 km	−12%	-
Charging infrastructure parameters			
Charger infrastructure costs	150 000 EUR	-	54%
Number of buses using charger	5 buses	-	−25%

EB will increase by 4% then there will be no economic benefit of using converted DB into EB. At least 4 electric buses are needed in operation in order to justify the investment of the charging infrastructure (excluding the grid connection costs).

4 Conclusion

The comparison of economic performance of the two bus alternatives – diesel bus and converted electric bus has been made using developed TCO model and similar TCO results for both alternatives are achieved. Nevertheless, the overall results of economic analysis are in favour of converted electric bus which apart from lower O&M costs provides additional benefits to the environment and extends the life of the used diesel bus. The conversion process is cost-effective as it reduces total TCO of the vehicle by 6% if infrastructure costs and external costs are not taken into the account.

The presented TCO results are satisfactory to justify the DB conversion into the EB; though variations of certain input parameters for O&M costs and investment costs of conversion have significant influence on the TCO results. Charging infrastructure investment costs do not have significant impact on economic viability of the diesel bus conversion to electric bus due to the fact that the charging infrastructure can be used by number of vehicles over its lifetime thus significantly reducing the cost burden per vehicle.

Methodology offered in this research can be used as a framework for local authorities and transport operators, on the bases of which it is possible to concretize TCO model and to assess the impact of critical variables on the life cycle cost of the bus.

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