



Decision-Making Process for Choosing Technology of Diesel Bus Conversion into Electric Bus

Kristine Malnaca^{1,2(✉)}, Mikhail Gorobetz^{1,3}, Irina Yatskiv (Jackiva)²,
and Aleksandr Korneyev³

¹ JSC Ferrus, 90 Gramzdas, Riga LV1029, Latvia
Malnaca.K@tsi.lv

² Transport and Telecommunication Institute,
1 Lomonosova, Riga LV1019, Latvia

³ Riga Technical University, 1 Kalku, Riga LV1658, Latvia

Abstract. Many local public transport authorities and operators are in need of replacing ageing bus fleet with cleaner and more sustainable vehicles in order to meet standards, increase efficiency and reduce transport related emissions. There is a wide choice of technologies for urban bus operators in the market including electric buses but at the same time new vehicles beyond lower emission Euro VI diesel buses are still a challenge for transport operators due to high acquisition costs and lack of charging infrastructure. The alternative proposed is to convert used diesel city bus into electric bus. Decision-making process for choosing technology of the bus conversion requires thorough assessment of possible solutions from the technical, operational, and economic point of view under the given conditions and constraints. Within the framework of this research, mathematical models are developed for assessing the efficiency of an electric vehicle on the basis of various criteria which affect life cycle costs. The models include the definition of functional dependencies and dynamic performance equations of a diesel bus and a converted electric bus. The results help to choose the most suitable parameters of the traction motor's torque and power under the given conditions and determine the most suitable battery type and capacity for the selected bus route. Total Cost of Ownership model is utilized in the decision-making process to determine economic viability of a technological solution to convert a diesel bus into an electric bus. The proposed methodology is tested in the case study.

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

1 Introduction

The European Commission's low carbon economy roadmap suggests that emissions from transport could be reduced to more than 60% below 1990 levels by 2050 [1]. One of behavioral changes identified that contributes to the de-carbonization of transport is the use of electric vehicles.

Following the European Commission's 2016 Strategy for Low Emission Mobility [3] many local public transport authorities and operators are in need of replacing ageing bus fleet with cleaner and more sustainable vehicles in order to meet standards, increase efficiency and reduce transport related emissions. There is a wide choice of cleaner fuel and engine technologies for urban bus operators in the market including electric buses but at the same time new vehicles beyond lower emission Euro VI diesel buses are still a challenge for public transport operators due to high acquisition costs of a new vehicle and lack of charging infrastructure. The alternative proposed is to convert used diesel city bus into electric bus which would significantly reduce the harmful impact of the used diesel bus on the environment and improve performance of the vehicle. Diesel bus (DB) conversion into electric bus (EB) can be realized using different technologies. In order to choose optimal solution of the bus conversion a thorough assessment of possible alternatives from the technical, operational, and economic point of view is necessary taking into account given conditions and constrains.

This paper explains the decision-making process for optimum technology selection of a diesel bus conversion into an electric bus where main technical and economic performance indicators are identified and assessment of alternatives is performed.

2 Methodology

2.1 The Decision-Making Process for Choosing the Optimum Technology

Before converting used DB into EB it is important to assess the technical, operational and economic performance of the existing vehicle by estimating the key characteristics of a motor (torque, speed, power), the basic physical characteristics of the movement (distance, speed, acceleration), and economic performance indicators. Economic efficiency in this study is assessed by calculating life-cycle cost of the bus which later can be used for comparison purposes among possible alternatives.

Once the values for key characteristics of the movement and the motor are obtained, possible configurations of EB can be defined. Alternatives are modelled, and it allows to assess characteristics of an electric motor. Values of the physical characteristics of the movement and the motor are important for selecting the battery type and capacity, which in turn has a great impact on the cost of the bus. The decision-making process for choosing the optimum technology of conversion is explained in Fig. 1.

Mathematical models and algorithms developed in this research are the following

- models of a diesel engine and an electric engine;
- model of an automatic gearbox and reduction gear;
- models of a generic bus, DB, and EB;
- model of a route for simulation;
- analytical models for DB and EB dynamics evaluation;
- algorithms for DB and EB motion simulation;
- algorithm for simulation of a bus movement at the predefined route;
- model and algorithm for the battery selection for EB.

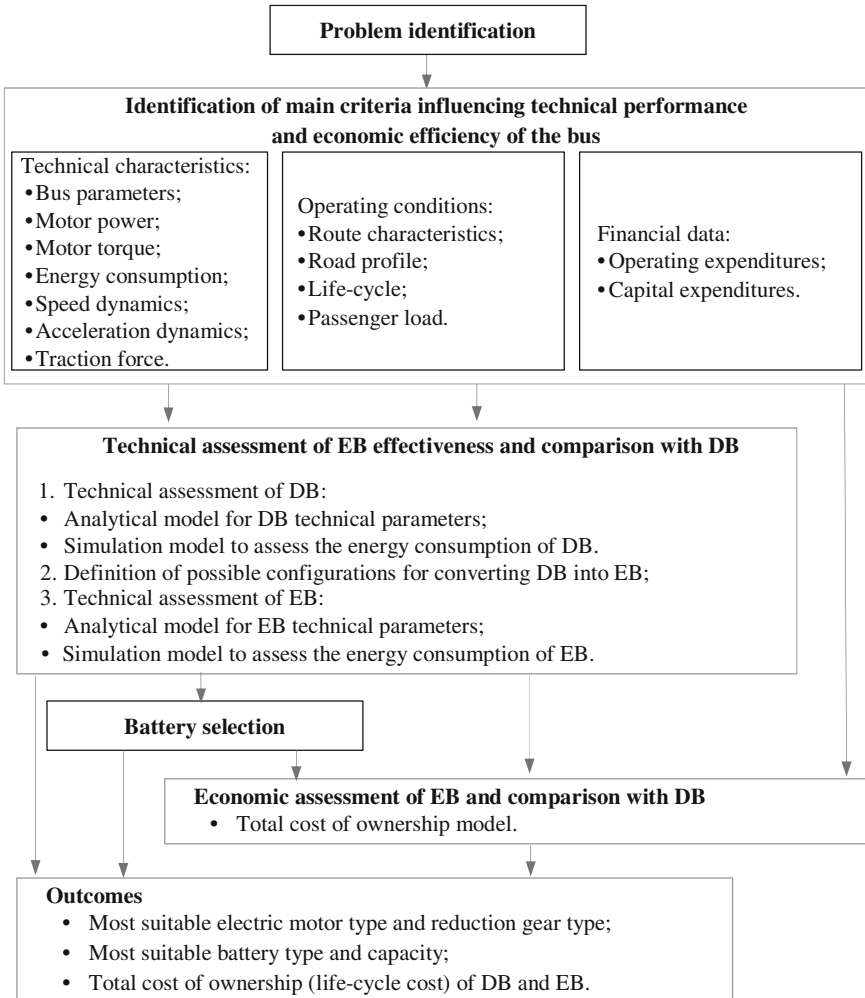


Fig. 1. Decision-making process for choosing technology of DB conversion into EB

The generic algorithm for the technical assessment has the following steps:

1. Use analytical model to evaluate technical parameters of DB: speed dynamics $v(t)$, acceleration dynamics $a(t)$, energy consumption $C(v)$, maximal slope $s(v)$, motor power $P(v)$, motor torque $T(v)$ and bus motion force $F(v)$.
2. Use simulation models of DB with different routes to assess the consumption of DB with different loads.
3. Define possible configurations as alternatives for conversion of DB into EB—reduction ratio of the rear axle, electric motor's nominal torque, nominal power, nominal rotation speed, battery types and capacity.

4. Use analytical model to evaluate conversion alternatives: speed dynamics $v(t)$, acceleration dynamics $a(t)$, energy consumption $C(v)$, maximal slope $s(v)$, motor power $P(v)$, motor torque $T(v)$ and bus motion force $F(v)$.
5. Use simulation models of EB with the same routes and the same set of different loads as for DB.
6. Use optimization model and algorithm for the battery selection.

2.2 The Main Models and Algorithms

The objective of **analytical models for DB** is to evaluate the dynamics of DB using the traction-speed parameter evaluation technique [5]. The method uses the DB model that inherits the generic bus model and includes models of the diesel engine and an automatic gearbox, and reduction gear.

Input parameters are: $TE_D(\omega) = \{t_1(\omega_1), \dots, t_n(\omega_n)\}$ —empiric values of the engine torque, $l \in \mathbb{R}$ —length of the bus, m; $w \in \mathbb{R}$ —width of the bus, m; $h \in \mathbb{R}$ —length of the bus, m; $m_0 \in \mathbb{R}$ —self mass of the bus, kg; $m_1 \in \mathbb{R}$ —max load mass of the bus, kg; $w_t \in \mathbb{R}$ —width of tire, m; $h_t \in \mathbb{R}$ —relative height of tire; $r_t \in \mathbb{R}$ —internal radius of tire, inch; $\alpha \in (0, 1) \in \mathbb{R}$ —aerodynamics frontal resistance ratio, Ns^2/m^4 ; $\varphi \in (0, 1) \in \mathbb{R}$ —road surface resistance ratio, m.

The outcomes of the analytical models are sets with momentary values of F_T —traction force of the bus; v velocity of the bus; F_f road friction force; F_a aerodynamic resistance force; \mathbb{D} dynamic characteristic; ζ_{max} maximal slope; a acceleration of the bus; t time travelled by the bus at the route stage; $P_D \in \mathbb{R}$ —momentary value of the engine power; C consumed energy. These sets represent the dynamic of DB [4]: speed dynamics $v(t)$, acceleration dynamics $a(t)$, energy consumption $C(v)$, maximal slope $s(v)$, motor power $P(v)$, motor torque $T(v)$, and bus motion force $F(v)$.

The goal of the motion simulation model for DB is to obtain key performance indicators of DB on the defined route using the specific developed algorithm. The route model R is represented by following parameters: $n_R \in \mathbb{N}$ —number of passenger stops; $l_R \in \mathbb{R}$ —total length of the route; $t_R \in \mathbb{R}$ —average time for movement between stops; $w_R \in \mathbb{R}$ —waiting time for passengers embark/disembark; $v_R \in \mathbb{R}$ —average motion speed for movement between stops; $s_R \in \mathbb{R}$ —average distance between two stops, where

$$s_R = \frac{l_R}{n_R - 1}, \quad (1)$$

$$v_R = \frac{s_R}{t_R - w_R}. \quad (2)$$

Input parameters for simulation are dt —time step for simulation and v_{max} —maximal speed to accelerate.

To obtain the comparable results of DB simulation with EB simulation the fuel consumption of DB is converted to the mechanical energy in kWh, taking into account the efficiency rates of the DB equipment: diesel motor, transmission, reduction gear etc. Thus, the main outcomes of the simulation for each route are $C \in \mathbb{R}$ —consumed

energy, kWh, $\theta_C \in \mathbb{R}$ —relative consumed energy per distance unit, kWh/km and $\max(v) \in \mathbb{R}$ —maximal velocity of the bus on the route, m/s.

It is obvious that various **different technical configurations of DB conversion into an EB** are possible. However, only two components are the most important for traction of the bus in general. These components are the motor and reduction gear. The simplified traction structure of DB is presented in Fig. 2. The blocks with the dashed outline in Fig. 2 are not parts of the traction system, but these components are necessary as power and control sources of the bus traction system. The different auxiliary systems have influence on the total energy consumption of the bus, but have no significant direct impact on the bus traction.

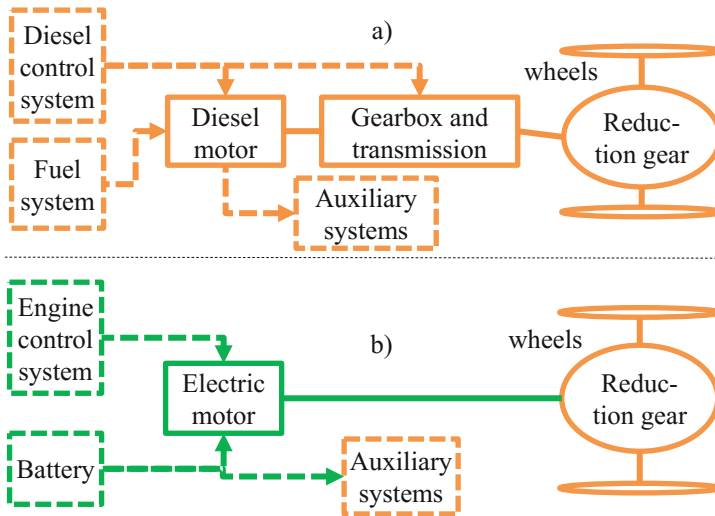


Fig. 2. Simplified traction structure of **a** a diesel bus and **b** an electric bus

As EB has no gearbox it is important to select the most suitable transmission rate of the reduction ratio for the stable and balanced motion of EB. Also, the power source (battery) should have the capacity, voltage and current characteristics to fit the bus. The control system is important too, but it requires the development of optimal control algorithms that is out of the scope of this paper.

Thus, the main outcomes of this step are different configurations (alternatives A) of the EB traction system represented by a Cartesian product sets of possible motors $M = (M_1, \dots, M_k)$ and $R = (R_1, \dots, R_p)$, i.e. $A = M \times R = (<M_1, R_1 >, \dots, <M_k, R_p >)$.

The objective of **analytical models for EB** is to evaluate the dynamics of each alternative of the EB configuration using the similar traction-speed parameter evaluation technique as for DB. The method uses the EB model that inherits the generic bus model and includes models of the electric engine and reduction gear. Input mechanical parameters are the same except $TE_D(\omega)$. But additionally for EB the following parameters are defined [8]: $P_{\max_E} \in \mathbb{R}$ —maximal power of the engine, kW;

$T_{\max E} \in \mathbb{R}$ —maximal torque of the engine, N.m; $P_{nom E} \in \mathbb{R}$ —nominal power of the engine, kW; $T_{nom E} \in \mathbb{R}$ —nominal torque of the engine, N.m; $\eta_E \in \mathbb{R}$ —efficiency rate of the engine; $I_{nom E} \in \mathbb{R}$ —nominal current of the engine, A; $U_{nom E} \in \mathbb{R}$ —nominal voltage of the engine, V; $\omega_{nom E} \in \mathbb{R}$ —nominal rotation speed of the engine, rpm; $J_E \in \mathbb{R}$ —inertia value of the engine, N.m.

The outcomes of these models represent speed dynamics $v_x(t)$, acceleration dynamics $a_x(t)$, energy consumption $C_x(v)$, maximal slope $s_x(v)$, motor power $P_x(v)$, motor torque $T_x(v)$ and bus motion force $F_x(v)$ of each EB configuration $x \in A$.

The goal of **the motion simulation for EB** is to obtain key performance indicators of each EB configuration $x \in A$ on defined routes using the specific developed algorithm. In order to obtain the comparable results the same routes are used as for the simulation of DB. Input parameters for simulation are dt —time step for simulation and v_{\max} —maximal speed to accelerate. Main outcomes of the simulation for each route and each configuration are $C \in \mathbb{R}$ —consumed energy, kWh, $\theta_C \in \mathbb{R}$ —relative consumed energy per distance unit, kWh/km and $\max(v) \in \mathbb{R}$ —maximal velocity of the bus on the route, m/s.

The goal of **optimization model for battery selection** is to select the battery type and capacity with minimal costs under predefined constraints.

$$F = \psi(X, B, C_{AC}, A) \rightarrow \min, \quad (3)$$

where F —total costs of the battery; X —set of input parameters; $B = (b_1, b_2, \dots, b_n)$ —set of n battery types; $A \in (\alpha_1, \alpha_2, \dots, \alpha_n) \in \{0, 1\} \in \mathbb{Z}$ —selection of the battery type from the battery type set; $C_{AC} \in \mathbb{R}$ —capacity of the battery, kWh.

A set of input parameters X consists of S_d —planned annual travelled distance by bus, km; c —consumption ratio of the bus, kWh/km; L —bus lifecycle, years; d —number of days per year of the bus exploitation, days; r —length of one route loop, km; U_c —charging voltage, V; U_d —discharging voltage, V; t_c —planned charging time after each loop, minutes.

For each battery type $b_i \in B$ the parameters $l_{AC} \in \mathbb{N}$ —maximum number of full charge cycles; $I_{\max AC} \in \mathbb{R}$ —relative maximal charge current of the battery per capacity, C; $\varpi_{AC} \in \mathbb{R}$ —relative capacity of the battery per weight, Wh/kg; $c_{AC} \in \mathbb{R}$ —relative costs of the battery per capacity, EUR/kWh are set for the selection.

The model for optimal battery selection is implemented in a Web environment and can be adjusted to the user needs.

Total Cost of Ownership (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 DB and the converted EB. The comparison of the results allows to assess economic viability of the proposed technology of DB replacement with the EB for public transport services in the urban environment [6].

The TCO model is presented in detail in the paper by Malnaca, Yatskiv [6] and includes the vehicle costs, the charging infrastructure costs, and external costs:

$$TCO = CInv(bus) + CInv(charger) + CInv(grid) + C(O\&M) + I * C(ext), \quad (4)$$

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. Environmental costs are calculated as follows:

$$C(ext) = C(CO_2) + C(NO_x) + C(PM), \quad (5)$$

where $C(CO_2)$ —costs of carbon dioxide emissions; $C(NO_x)$ —costs of air pollution (nitrogen oxides); and $C(PM)$ —cost of particulates.

For the comparison purposes TCO is expressed in Equivalent Annual Cost (EAC) as cost per kilometer (€/km), using a discount rate of 4% [2].

3 Case Study of Decision-Making Model Application

3.1 Model Initialization and Parametrization

The developed decision making steps are carried out for the conversion of the diesel bus Ambassador ALE 120-205/225 used in the mid-size city in Latvia as a public transport.

Technical assessment and economic analysis includes both mathematical and expert estimations regarding model development. A number of model variables requires expert evaluation based on specific location, situation, and mostly on availability of necessary infrastructure for the use of EB, whereas other items are included on constant bases.

Variables used in the models and their values are given in the Table 1. The variables are identified as the main indicators of technical performance and cost-effectiveness, which are the measures of outcome. All prices are given net of VAT.

Torque-rotation speed curves are obtained from the technical specification of the bus and the fragment is provided in the Table 2. The bus may be equipped with ISBe⁴ 205 or ISBe⁴ 225 diesel motor. For the simulation 2 routes are used with 6 different relative loads of the bus: 1—an abstract city route (25 stops/an average 1-minute time between stops); 2—a part of an intercity or the city route (70 km/h speed limit).

Different EB configurations are compared combining the sets of 6 motors and 3 reduction ratios and obtaining 18 alternatives. Parameter of energy consumption rate is compared with the same parameter of DB with ISBe⁴ 205 and ISBe⁴ 225 engines. Thus, influence of three different reduction ratios are tested: 4.88 ratio is the same gear as the DB has, 5.83 ratio is mostly used in similar EB, 8 ratio is mostly used in high torque EB. Six different most popular electric motors that are available in the market are simulated. Taking into account big amount of simulation and various criteria, it is assumed that EB is working at the nominal voltage in this study.

Table 1. Models' variables and their values.

Type	Variable	Value (DB)	Value (EB)
Technical	Self-mass	8900 kg	1.2 kWh/km
	Full mass	14,440 kg	
	Dimensions (length, width, height)	11,950 × 2500 × 2920 mm	
	Wheel and tire size	265/70/R19.5	
	Energy consumption	10.4 MJ/km (29 l/100 km)	
	Charging and discharging voltage	650 V	
	Drag coefficient	0.7	
	Aerodynamics frontal resistance rate	0.3	
	Transmission efficiency rate	0.9	
Operational	Useful life	10 years	7 years
	Length of one loop (distance travelled between charging)	34 km	
	Planned charging time after each loop	9 min	
	Road surface resistance rate	0.02	
Financial	Investment cost	200,000 €	196,700 €
	Energy price	1.00 €/L	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	Investment cost of charging infrastructure	n/a	150,000 €
Infrastructure	Charging infrastructure maintenance	n/a	1,000 €/year
Grid	Investment cost of grid connection	n/a	30,000 €
Connection	Transmission power maintenance	n/a	19.56 €/kW/year
	Electricity transmission tariff	n/a	0.02129 €/kWh

The estimated price of the converted EB is based on the remaining value of the 7-year old DB and the incremental cost of the conversion (the difference between the cost of battery, electric drive, other supplementary materials, and labor costs and the re-sell value of diesel engine and transmission system).

Table 2. The fragment of torque-rotation speed specification of DB.

ω_D , rpm	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000	...
TE_D — ISBe ⁴ 205, Nm	700	725	750	750	750	750	750	750	732	712	690	...
TE_D — ISBe ⁴ 225, Nm	700	775	850	850	850	850	850	850	840	828	790	...

In this study, the average travelled distance of the bus is assumed to be 200 km a day without returning to the depot. Fast charging infrastructure, also known as opportunity charging, with pantograph is selected in this analysis based on the results obtained from motion simulation model and battery selection model. As concluded by Malnaca, Yatskiv [6], smaller battery means less initial investment cost, less weight, and more room inside the bus for passengers.

The maintenance expenses of electric drive system are expected to be 30% less compared to combustion power transmission system because it requires less frequent service maintenance.

3.2 Modelling Results and Discussion

Average values of energy consumption rate of the diesel bus Ambassador ALE 120 is 1.8073 kWh/km for ISBe⁴ 205 engine and 1.798 kWh/km for ISBe⁴ 225 engine. Both models—analytical and simulation—provides similar results. Obtained criteria values are compared with different configurations of EB.

The average energy consumption of EB is estimated at 1.2 kWh/km in the conditions typical for the average mid-size city in a relatively flat area using the mathematical model which was created within the study to evaluate the effectiveness of EB. The efficiency of EB is higher for lower load values and lower for higher load values for the city route 1. The average energy efficiency is 31%.

The obtained simulation data and the results of acceleration dynamics analysis for each load allow selecting the most efficient configuration of EB.

Table 3 shows the comparison of average energy consumption of different configurations of EB and DB. The most efficient configurations of EB are motors 2300 Nm/200 kW/2350 rpm and 2600 Nm/250 kW/3500 rpm.

Analysis of the dynamics of EB allows comparing different reduction ratios of the rear axle for these motors. Reduction ratio 8.00 shows better maximal slope values, but in most cases it cannot achieve the maximum speed of 70 km/h within the maximal power, torque and rotation speed limitations. Also, acceleration values are higher and that may cause a discomfort for passengers. Reduction ratio 4.88 has higher energy consumption for the acceleration and lower maximal slope parameters. Reduction ratio 5.83 shows better parameters comparing to other reduction ratios, because it is able to achieve maximal speed of 70 km/h within the maximal power and the acceleration is

Table 3. Average energy consumption and its improvement by bus configurations.

Bus configuration (motor type, reduction gear ratio)	Average consumption rate EB, kWh/km	Average consumption rate DB, kWh/km	Improvement, %	
1800/250/3200, 4.88	1.229	1.803	31.80	
1800/250/3200, 5.83	1.232		31.66	
1800/250/3200, 8.00	1.233		31.58	
2100/200/3240, 4.88	1.232		31.67	
2100/200/3240, 5.83	1.232		31.65	
2100/200/3240, 8.00	1.234		31.55	
2200/250/3500, 4.88	1.234		31.57	
2200/250/3500, 5.83	1.234		31.54	
2200/250/3500, 8.00	1.235		31.48	
2300/200/2350, 4.88	1.219		32.38	
2300/200/2350, 5.83	1.220		32.30	
2300/200/2350, 8.00	1.221		32.26	
2600/250/3500, 4.88	1.220		32.31	
2600/250/3500, 5.83	1.222		32.21	
2600/250/3500, 8.00	1.223		32.14	
2700/250/3525, 4.88	1.235		31.51	
2700/250/3525, 5.83	1.235		31.49	
2700/250/3525, 8.00	1.237		31.41	
Average:	1.229		1.803	31.81

faster than for 4.88. However, acceleration values are not so high and the change is smoother than for 8.00. The consumption is lower than for 4.88 and approximately the same as for 8.00. The recommended gear reduction ratio for the rear axle is 5.83. The recommended motors for the Ambassador EBs are provided in the Table 4.

Table 4. Recommended types of motor.

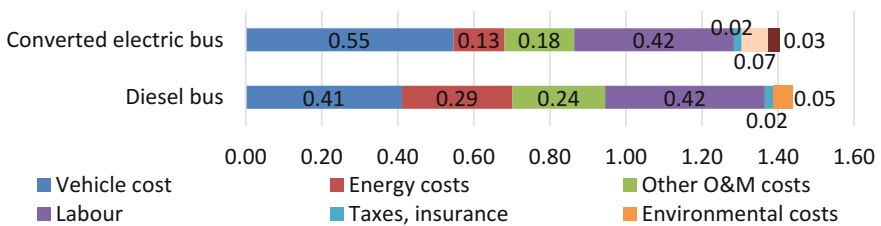
Motor type	Peak power (kW)	Cont. power (kW)	Peak torque (Nm)	Cont. torque (Nm)	Max operating speed (RPM)	Efficiency rate
2300/200/2350	200	150	2300	1230	2350	0.95
2600/250/3500	250	150	2600	969	3500	0.95

The recommended battery type is MpCO battery with 91 kWh capacity and 910 kg weight under the given constraints and operating conditions. The output of optimization model for battery selection is shown in the Table 5.

Table 5. Optimization results for battery selection.

Battery type	Capacity, kWh	Weight, kg	Cost, EUR	Max current, A
MpCO	91	910	70,707	2.99
LCO	91	758	81,900	2.99
LTO	91	1517	127,400	2.99
LFP	294	2262	147,000	0.93
NMC	588	4900	552,800	0.46

The main results of *TCO* analysis are shown in the Fig. 3. The calculated *TCO* of the diesel bus is 1.44 €/km, which include all costs related to owning, operation and maintenance of the bus and environmental costs 0.05 €/km. As concluded by Malnaca, Yatskiv [6], the price of the 7-years old DB converted into the EB is similar to the new DB, 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. 3.** *TCO* analysis results of DB in comparison with converted DB into EB (EUR) [6]

4 Conclusion

The results of the case study prove the workability of the developed decision-making model and its applicability to the task of selecting technology for DB conversion into EB. The importance and necessity of each step of the process are confirmed by the case study. The provided methodology allows to assess technical, operational and economic performance of the existing DB and to find the optimum technological solution for DB conversion into EB which would have the same or even better values of technical and economic performance indicators.

The results of the models of the case study show that the EB which is converted from the Ambassador diesel bus may be by 31% more energy efficient. Average energy consumption rate for the analyzed EB is 1.229 kWh/km, however it may vary from 0.96 kWh/km to 1.54 kWh/km depending on the route type and the load.

The overall results of technical and economic assessment are in favour of used DB conversion into EB. The selected technical configuration of EB allows to achieve significant energy efficiency, reduce *O&M* costs of the vehicle, provides additional benefits to the environment, and extends the life of the used DB.

Acknowledgements. The paper is based on the research that has been conducted in the framework of the project No1.1.1.1/16/A/267 ‘Development of economically justified technology of conversion of the traditional diesel city bus into the environmentally friendly electrobus funded from the ERDF, and was financially supported by the ALLIANCE Project (GA no.: 692426) funded under European Union’s Horizon 2020 research and innovation program’.

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