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# Fully Electric City Buses – The Viable Option

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**Abstract**—Key challenges in traffic systems are carbon footprint of the vehicles, local emissions, noise and congestion. Fully electric city buses offer a solution to these challenges in public inner city transport. At the same time, electric buses open up for a lower total cost of ownership (TCO) provided that the vehicle, charging infrastructure and new operating concepts are designed and considered together. This is based on the fact that high utilisation rates of the expensive battery systems can be reached in commercial electric city bus operation, as opposed to private electric passenger cars. Fully electric city buses can be seen as the first market-based introduction of electrically-driven road vehicles which is justified both in commercial and environmental terms. This paper presents a TCO tool which incorporates the previous factors into a single TCO model and is anchored to component, vehicle and traffic system analysis. Consequently, the model can be utilised in investigating the most economically feasible charging infrastructures and vehicle technology concepts for further development of the electric bus city traffic. The model indicates that a combination of shared opportunity charging systems with possibly multimodal transport components, and fully electric buses with small but high power capable batteries will provide the lowest TCO. Such electric bus systems provide the best added value when operated on city lines and operation sequences with the highest utilisation.

**Keywords**—*electric city buses, TCO, opportunity charging*

## I. INTRODUCTION

Mobility and transport, both private and commercial, are in the process of transformation. The key challenges faced in today's traffic systems are carbon footprint of the vehicles, local emissions and noise, and congestion. In addition, there are indications that the attitudes of consumers are changing from a desire to own a means of transport (a car) towards shared and easiness of transport. Traffic systems are thus not only experiencing technological change in terms of new vehicle technologies (e.g. electric vehicles, automated driving, and increasing connectivity) but in societal terms as well. The technosocietal change is moving traffic systems from non-smart and non-ecological mobility towards ecological smart mobility with increasing amount of clean vehicles, shared use and ICT services. [1]

Fully electric city buses have the potential to dramatically reduce the carbon footprint, local emissions and noise of public city transport. Combined with smart ICT

systems providing accurate timetables and options for the consumers, fully electric city buses can accomplish, in their part, an affordable and ecological inner city smart mobility. Recently, the Finnish Helsinki Regional Transport Authority (HRT) responsible for organising public transport in the Helsinki area announced that they are ramping up fully electric bus share being 1 % in 2015, 10 % in 2020 and 30 % in 2025 [2]. Similar guiding principles are being made in various major European cities. The feasibility of electric buses is being demonstrated within the Zero Emission Urban Bus System (ZeEUS) project funded by FP7 and coordinated by UITP [3].

Low carbon footprint of a fully electric city bus is obvious, provided that the electricity used for charging is CO<sub>2</sub> free, but accomplishing cost effectiveness requires careful systems engineering. The transformation towards electrification entails changes in value chains and business models established in the conventional way of operating city bus traffic. Techno-economic cost-benefit analysis is necessary for evaluating and also identifying the most potential city lines to be electrified and the types of system concepts and vehicle configurations that optimally serve the purpose. Such analyses have been previously carried out by, for example, Lajunen [4].

The paper introduces a total cost of ownership model that takes into account the different types of fully electric city bus powertrain dimensioning and different charging concepts. With this model, the economic viability of electric city buses and different charging concepts are shown and the uncertainties related to certain parameters are discussed through a sensitivity analysis. The novelty of the paper is to bring together on-going vehicle technology analysis and eBus system demonstration with the TCO calculation tool.

## II. INVESTIGATING THE POTENTIAL & OPTIMISING THE VEHICLE

Fully electric city buses require a range of e-components such as inverter, electrical energy storage (e.g. battery), charger and several auxiliary components like power steering pump etc. that all will decrease the overall energy efficiency. Figure 1 (top) shows an example of how the electric energy taken from the battery is consumed in an electric bus. The values in the energy distribution diagram are from dynamometer test cycle using VTT's prototype electric city bus (Figure 1, bottom) [5]. The test cycle represents an

actual operation line in Helsinki region. The length of the cycle is 9.14 km with average speed of 24 km/h. The lightweight bodied bus had an energy consumption of 0.61 kWh/km in the cycle (5.55 kWh in total). The driving resistances and the effect of vehicle mass are simulated by the dynamometer, initially founded by weighing the vehicle and with coastdown tests. The weight of the vehicle was 12 345 kg.

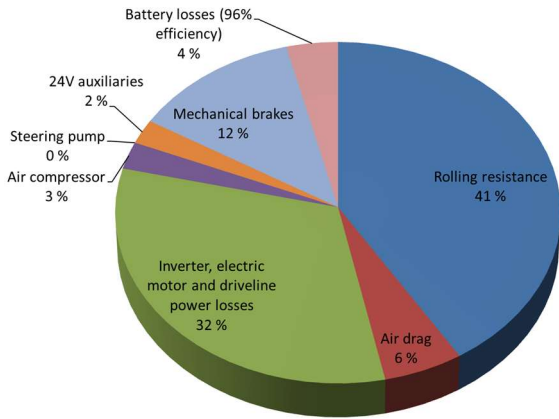


Fig. 1. Top: Distribution of energy consumption in VTT's prototype electric city bus. Bottom: VTT's prototype electric city bus.

The energy consumption in an electric city bus can be studied using a simulation model of the vehicle [6]. In this paper, an example of this kind of vehicle simulation model is briefly discussed. The model can be used for finding an overall energy efficient solution. Different combinations of the powertrain components can be varied easily and their effect on the consumption in different driving cycles evaluated. The modelled vehicle is VTT's prototype bus [5]. The baseline model has been verified against the actual vehicle. The model consists of vehicle, driveline mechanics and e-component models. The required level of model complexity depends on the optimisation targets. For energy efficiency optimisation, the energy flow simulation from battery to different subsystems and components is essential.

In addition to vehicle engineering, the requirements for fully electric city buses should be defined from even wider scope taking also into account the roles of a bus operator, the transport authority, local electric utility, and bus routes themselves. The operation environmental conditions must be addressed as well. In Finland, the same bus should operate in -30 °C and also in +30 °C. This temperature range and the required vehicle thermal management introduce significant

additional energy consumption which needs to be optimised. Cabin heating can consume more than a double of the energy used for traction. Using the authors' simulation model, dimensioning the powertrain components such as battery, drive motor or mechanical driveline can be done. For optimising the battery, for example, many aspects need to be considered such as lifetime as maximum cycles and calendar years, maximum current, maximum capacity, cycling depth, and aging when temperature varies. All of these are heavily dependent on the desired bus route and the concept of operation.

To optimise the overall vehicle level energy management (including thermal management), simulation of related control systems and thermal energy flows need to be included. Therefore, authors are using this approach for studying the optimal energy management strategies. On the top of already verified powertrain model, cooling circuit model of the powertrain components was added, from which exploiting waste heat energy flows can be studied. The model was further augmented with a cabin model, where heat flows from surrounding environment, heating devices and powertrain components can be evaluated.

This vehicle level work including measurements and modelling is then combined with charging infrastructure and operation concepts (system level concepts) for the purpose of calculating a total cost of ownership of fully electric city buses.

### III. SYSTEM-LEVEL CONCEPTS

There are basically two different approaches or disciplines in dimensioning electric powertrains and adjoining charging systems for fully electric city buses: i) a long-range bus design with a large battery charged with low power during night time and/or midday breaks, and ii) a short-range bus design with a small battery charged with high power at purposely situated automatic high-power charging points, see e.g. [7]. It is important to understand the key characteristics of these two design types because the cost structures, operation concepts, and most importantly value chains and business models in traffic system design and operation are very different between the two alternatives.

The advantage with long-range electric buses is that they are similar to conventional diesel buses. The long range enables diesel bus like operation with an addition of charging at a specific site, e.g. a depot. The charging interconnection is made by standardised industrial alternating current (AC) plugs and sockets, standard automotive charging plugs and sockets, or DC fast charging systems. All of these are readily available and can be purchased by operators themselves. Thus, the procurement and operation of a long-range eBus is simple: it needs to have enough of range and the charging power has to be just high enough for night time/daybreak charging. However, there are disadvantages in long-range eBuses that limit their viability in large-scale roll-out. First, they are limited in range by their battery size and thus cannot operate on the heaviest operation sequences where the daily energy requirement exceeds the capacity of the battery. Second, the

high cost of the bus as well as the weight and volume of the battery limit both the available passenger capacity and energy efficiency.

The cost of an eBus can be significantly decreased by reducing the battery capacity (size). Such a cost effective short-range eBus ultimately leads to the need of constructing a purposely-designed and built automatic high-power charging infrastructure (utilising either automated mechanical interconnections or inductive charging). Such a charging infrastructure concept is described in Figure 2 where high power automated charging is provided at the ends of a single bus route. While the low cost (and more energy efficient design) is the advantage of the short-range eBus, the charging infrastructure requirement is unconditional. The appropriate charging infra can require considerable engineering and involvement with city planning. Changes in value chains, business models and in the conventional way of operating bus traffic systems may be required. Smarter traffic system designs and operations are required to fully realise the benefits of electric city buses. A charging infrastructure has to be purposely designed for every electric bus route. The first city bus lines to be electrified will require the largest relative investment in the charging infrastructure. Once the roll-out of electric bus systems proceeds and the number of charging stations increases, each individual charging station can serve a larger number of buses (or bus lines) up until the point where the charger is fully utilised. This will in a natural way advance the extension of the stationary charging infrastructure.

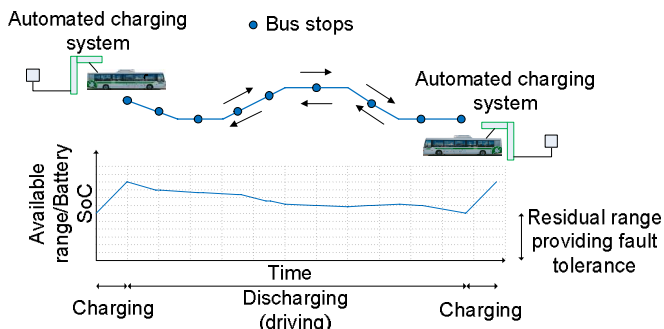


Fig. 2. Concept for automatic charging at the end of the lines

Implementation of high-power automatically connecting charging infrastructure (opportunity charging) at the end of the lines and/or along the routes is, along with modern traction batteries, the enabling technology for cost effective electric city bus traffic. There are several aspects that need to be addressed to make this a wide spread reality:

- Standardisation of the charger interconnection and communication between charger and eBus
- Business models for charging infrastructure ownership and shared use in multimodal transport
- Design for the locations and power levels for the charging points within bus traffic system

- Cost effective short-range city bus designs with high charging power capability
- Considerations for redundancy and failure tolerance of the charging infra and traffic system
- Proven calculations of lower TCOs of electric bus traffic vs. diesel bus traffic
- ICT systems, connectivity with the vehicles and charging infrastructure (charging and fleet management)

#### IV. TOTAL COST OF OWNERSHIP

The main costs related to operating bus systems are labour costs of the drivers, as well as capital costs of the vehicle and costs of fuel and vehicle maintenance. In this study, the labour costs are assumed to be equal between buses running on different fuels such as diesel vs electricity. This is true as long as the size of the bus fleet is unaltered. In this respect, the present analysis differs in approach from that of Lajunen [4], who increased the size of the electric bus fleet in comparison with conventional and hybrid buses. This will kill the economy for the fully electric bus case. The present paper assumes very strict approach aligned with strategies of Public Transport Authorities (PTA) and bus operators. The following requirements need to be fulfilled by electric bus systems in order for them to be successful:

- the size of the bus fleet must not be increased when replacing conventional buses with electric ones,
- the operability of the electric buses must be at the same level as that of the conventional buses, and
- the level of service, reliability and passenger comfort need to be the same or better compared with conventional buses.

The approach of the present paper is to calculate the Equivalent Annual Cost (EAC) for operating a fleet of electric buses. The EAC gives the cost per year of owning and operating the relevant assets and takes into account the expected entire lifespan of the vehicles and critical system components such as charging equipment. A TCO calculation was carried out where six different fully electric buses were compared with three different diesel buses. The basic assumptions common to all types of vehicles were: residual value at the end of the service life is zero for both the vehicle and the battery, interest rate is 5%.

##### A. The model and parameters

The EAC consists of the components for the vehicle (including the traction battery) and charger, together with energy, service & maintenance, and urea cost:

$$EAC = EAC_{Vehicle} + EAC_{Charge} + Energy + S\&M + Urea$$
,  
 where the EAC terms take into account the net present value through annuity factors. The total cost of ownership (€/km) is calculated from the EAC by dividing it by the number of annual operation kilometres.

The purchase prices of the vehicles were as follows: Diesel EEV 215.000 €, diesel light-weight EEV 225.000 €, diesel Euro VI 240.000 € (all from [8]), electric bus type (1) 300.000 € and electric bus type (2) 320.000 €, both without the battery. . The service life (depreciation time) of all buses is 12 years, and for the battery system in electric buses according to the cycle lifetime estimate. The service life (depreciation time) for the charging equipment was taken as 10 years.

The cost of service & maintenance and urea are assumed to be constant annually. Energy consumption equals diesel for conventional buses and electricity for eBuses. The optimal energy consumption of electric bus traction is assumed to be 0.65 kWh/km and 0.2 kWh/km is assumed for air conditioning & heating. These “ideal” consumptions are then increased by different factors such as chassis and battery weight and efficiencies related to the electric vehicle powertrain, battery, auxiliaries, energy management and charging. These are taken into account by calculating an effective efficiency giving the total consumption (kWh/km) for each electric bus and powertrain configuration calculated here.

For the analysis, two main electric bus types are calculated: (1) a long-range and a (2) short-range bus type. For these, different battery systems were calculated: i) large energy-optimised lithium iron phosphate (LFP) battery for the long-range bus, and ii) small power-optimised lithium titanate (LTO) or LFP battery for a short-range eBus. Further, the long-range bus (1) has two vehicle variants: baseline and optimistic, whereas the short-range eBus (2) has three variants: baseline, optimistic and pessimistic. The variants serve the purpose of sensitivity analysis in terms of the vehicle, where vehicle efficiency through energy consumption and therefore range affect the total performance and economy of the bus.

The different calculated bus variants, including the battery type and size as well as the charging equipment cost are summarised in Table I. In the header for each column, “B” stands for the *baseline* vehicle variant, “O” for *optimistic* and “P” for *pessimistic*. Each bus variant is assigned consumption (kWh/km) according to “unidealities” as shown in the table. It is assumed that each type (1) bus will have its own dedicated socket charger at bus depot. Shared use of the charging infrastructure is possible for bus type (2). The acquisition prices and maintenance costs for the charging infrastructure, as well as assumed annual maintenance costs for the electric buses are given in Table I as well.

Battery lifetime is a critical parameter in the cost structure. Cycle life of batteries is a complex question and depends in fundamental ways on several parameters in battery systems design, such as selected cell materials, quality of manufacturing and cell microstructure, thermal and electrical management of the battery pack, depth of discharge in individual load cycles, and the current (C-rate) of the duty cycle. Only cycle life of the batteries is considered in the present analysis and the effect of calendar life is neglected.

TABLE I. MAIN PARAMETERS USED IN THE TCO CALCULATION

Electric bus variants	Table Column Head					
	1 B	1 O	2 B LTO	2 O LTO	2 P LTO	2 B LFP
Battery type	LFP energy	LFP energy	LTO power	LTO power	LTO power	LFP power
Battery capacity kWh	280	280	60	60	60	120
Battery cost €/kWh	600	600	1 200	1 200	1 200	600
Eff. Battery weight penalty	0.93	0.93	0.96	0.96	0.96	0.96
Eff. Chassis weight	0.96	1	1	1	0.96	1
Eff. Powertrain	0.95	0.96	0.95	0.96	0.95	0.95
Eff. Battery	0.94	0.96	0.94	0.96	0.92	0.94
Eff. Charging	0.95	0.98	0.95	0.98	0.95	0.95
Eff. Auxiliaries	0.95	0.95	0.95	0.95	0.95	0.95
Eff. Vehicle energy managem.	0.95	0.98	0.95	0.98	0.93	0.95
Effective efficiency	68 %	78 %	74 %	81 %	68 %	74 %
Consumption kWh/km	<b>1.24</b>	<b>1.09</b>	<b>1.16</b>	<b>1.05</b>	<b>1.26</b>	<b>1.16</b>
Charger power (kW)	50	50	300	300	300	300
Charger unit price (k€)	20	20	250	250	250	250
N of buses one charger can serve	1	1	10	10	10	10
Charger service & manag / a (k€)	3	2	5	5	8	5
Bus service cost / a (k€)	8	6	8	6	9	8

Generally, cycle life (number of cycles before discarding the cell) increases rapidly when the State of Charge (SoC) window within which the cell is cycled becomes narrower. Alto the total amount of energy cycled through the battery is expected to increase when the  $\Delta$ SoC is reduced from full cycles. Cycle life is challenging to model in detail based on open literature data, because much of this information is proprietary to the battery cell manufacturers. One of the few sources found is the presentation from Alaküla [9]. The data from Alaküla is not scientifically sound, as no references or sources are given. While the general trend is correct, in the authors’ opinion the presentation in [9] on LFP and LTO cell cycle life is likely to underestimate the number of cycles at high  $\Delta$ SoC and overestimate at low  $\Delta$ SoC. An approximate cycle life dependency on  $\Delta$ SoC was prepared, based on the Alaküla data and the authors’ own best estimate. The dependency applied in the present analysis is shown in Figure 3. The data includes a baseline as well as upper and lower boundaries to be used as optimistic and pessimistic variants in the sensitivity analysis. It has to be stressed that the battery cycle life is just an educated estimate and validation with real experimental data would be highly relevant.

### B. Case: electrification of Espoo city line 11

The analysis was carried out for a concrete case, related to an on-going electric bus system project in the city of Espoo in Finland. This pilot demonstration of electric city buses is supporting HRT’s strategy on electric bus rollout. Veolia Transport Finland is the operator of the electric buses. The analysed case is electrification of Espoo city line 11, which is normally operated by 5 buses, has length of about 11 km (round-trip is thus 22 km). Three different daily operation sequences were covered: 6, 10 or 14 round-trips on the line, which give daily distances of 132 km, 220 km and 308 km, respectively. The annual kilometres were calculated assuming 330 operation days per year. The case with 10 round-trips (220 km daily) was selected to be the baseline, since this is the maximum distance that the type (1) baseline electric bus just barely manages to cover, given the consumption of 1.24 kWh/km given in Table I. The cases with 6 and 14 round-trips were used in the sensitivity analysis part to analyse the effect of daily mileage (vehicle utilisation) on the economy (TCO) of operation.

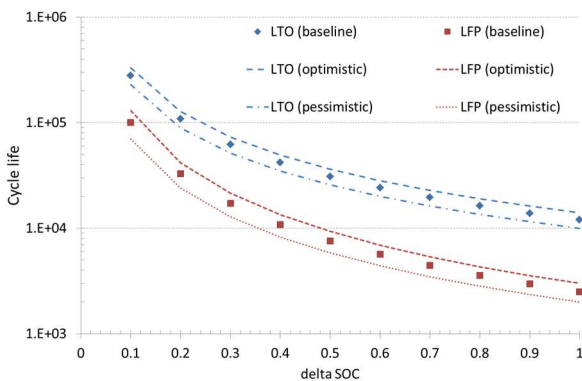


Fig. 3. Estimates of the cycle life dependencies on the  $\Delta$ SoC for LTO and LFP batteries.

Two charging stations rated at 300 kW were positioned on the bus line, one in each end. For each bus, the energy needed for one round-trip was calculated from the energy consumption, and the charging time needed at each charging point was calculated from this energy need. The full-power charging times for type (2) buses were between 2 and 3 minutes, which is feasible with a view to the PTA requirement that no extra time or buses are added due to electrification. There is actually still some margin to cover if the energy consumption is for some reason increased (e.g. a cold winter day) or one of the chargers might temporarily not be available. Type (1) bus (long-range) was not charged during the day.

The resulting  $\Delta$ SoC is closely related to the operation concept (charging power and time) and dimensioning of the battery (see Table I), and for the given set of parameters. For bus (1) the  $\Delta$ SoC = 100%, and for the bus types (2) in the range 11 – 23%.

### C. Sensitivity analysis

In order to chart the sensitivity of different key parameters in the calculated TCO, sensitivity analysis of the following parameters was carried out:

- daily distance (km)
- vehicle service life (depreciation time, y)
- battery price (€/kWh)
- battery lifetime (number of cycles)
- price of electricity (€/kWh)

The sensitivity was calculated for each parameter at a time, while keeping all other parameters in their baseline value. The three electric buses included in the sensitivity study were the baseline buses of type (1) “eBus 1 B”, and baseline buses “eBus 2 B LTO” and eBus2 B LFP” of type (2). The values used are shown in Table II.

TABLE II. MAIN PARAMETERS USED IN THE SENSITIVITY ANALYSIS

Table Head	Parameters in the sensitivity analysis		
	Pessimistic	Baseline	Optimistic
Daily distance (km)	132	220	308
Vehicle service life (y)	10	12	14
Battery price (€/kWh)	800 (LFP) 1600 (LTO)	600 (LFP) 1200 (LTO)	400 (LFP) 800 (LTO)
Battery lifetime	Ref. Figure 3		
Price of electricity (€/kWh)	0.13	0.10	0.07

### D. Results and discussion

The main results of the TCO analysis are shown in Figure 4 using the vehicle data in Table I and baseline values from Table II. It is emphasised that in Figure 4, the variants “pessimistic” and “optimistic” relate to *vehicle design*, that is, to different vehicle-level solutions which resulted in the slightly different effective efficiencies given in Table I.

The calculated TCO of operation (excluding the drivers labour costs) of the modern reference bus, Euro VI diesel is 0.85 €/km. The calculated TCO for Euro VI diesel bus is in line with the data from Nylund [8]. eBus type 1 (long range) is not economically competitive against the diesel buses; eBus 1 has a TCO of 1.15 €/km. The high cost is mainly due to vehicle cost, which includes the cost of the large battery. The short-range bus variants (2), on the other hand, turn out to be relatively competitive against the Euro VI diesel. The vehicle cost of eBus (1) is significantly lower than that of the long-range eBus. The cost of the charging infrastructure comes out quite equal for types (1) and (2), although they are of completely different types.

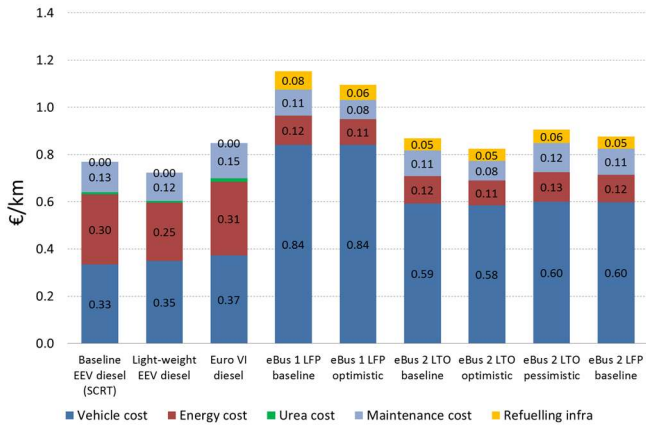


Fig. 4. TCO analysis on operation of electric city buses in comparison with conventional diesel buses (EEV and Euro VI). The labour costs of the drivers are excluded.

The sensitivity analysis cases calculated are shown in Figures 5 – 9. Figure 5 gives the results from varying the daily distance and is shown for each bus type in subgraphs A to D. Figure 6 shows the results when the vehicle service life (depreciation time) was varied. Figures 7 to 9 present the calculation only for the electric bus variants when varying battery price, lifetime and the price of electricity, respectively.

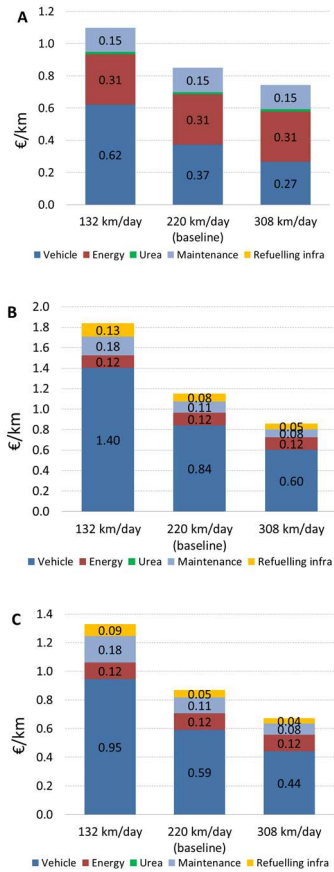


Fig. 5. Sensitivity of the TCO on the daily distance for different types of buses. A: Euro VI diesel, B: eBus 1 B, C: eBus 2 B LTO, D: eBus 2 B LFP.

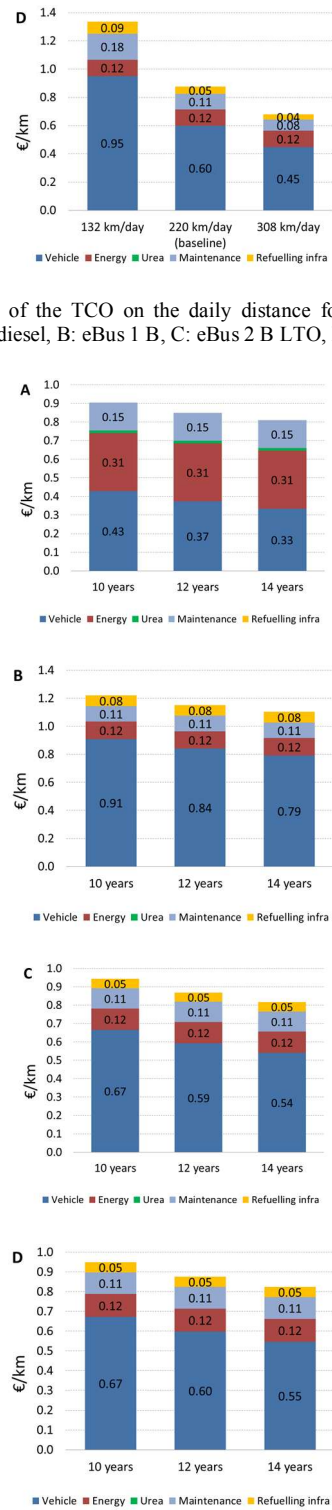


Fig. 6. Sensitivity of the TCO on the bus service life (depreciation time) to the TCO for different types of buses. A: Euro VI diesel, B: eBus 1 B, C: eBus 2 B LTO, D: eBus 2 B LFP.

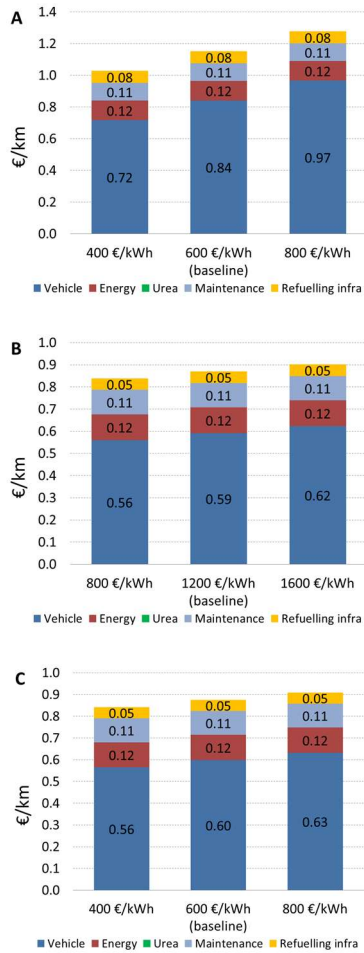


Fig. 7. Sensitivity of the TCO on the battery price for different types of electric buses. A: eBus 1 B, B: eBus 2 B LTO, C: eBus 2 B LFP.

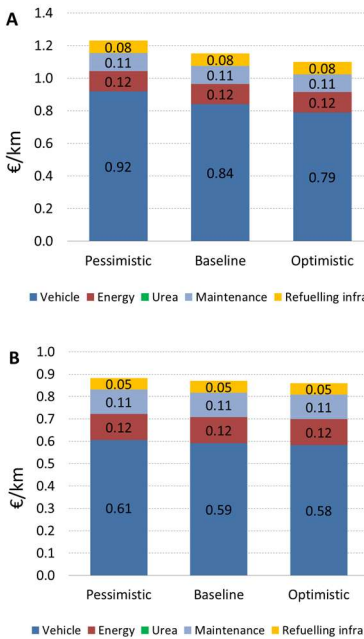


Fig. 8. Sensitivity of the TCO on the battery lifetime for different types of electric buses. A: eBus 1 B, B: eBus 2 B LTO, C: eBus 2 B LFP.

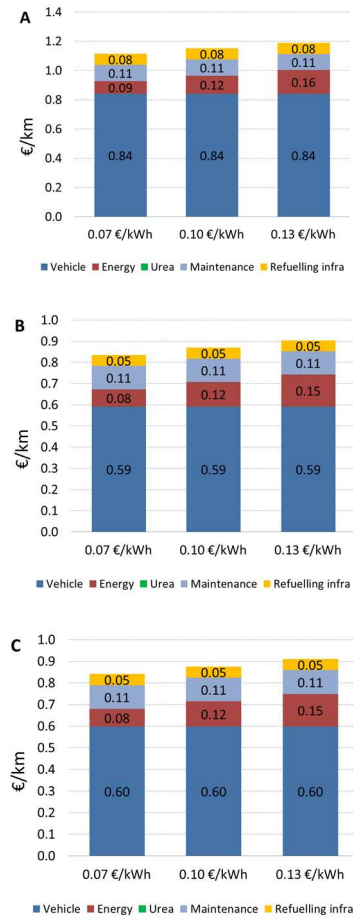


Fig. 9. Sensitivity of the TCO on the electricity price for different types of electric buses. A: eBus 1 B, B: eBus 2 B LTO, C: eBus 2 B LFP.

## V. DISCUSSION

Generally, the short-range eBus with a small battery and opportunity charging appears to be the concept that can successfully compete with conventional technologies in terms of operation costs of the fleet. It fulfills the PTA requirements stated earlier of flexible operation without the need to add extra buses into operation. Under the assumptions made in the calculation, both LTO and LFP appear to be potential battery technologies for this application.

It can be observed that increasing the daily mileage of the buses to 308 km (14 round-trips) decreases the cost of the



battery-driven buses much more than for the Euro VI diesel. The higher the utilisation and mileage, the more competitive the opportunity charging electric bus becomes. It is good to note in Figure 5B that the type (1) eBus actually cannot operate the largest distance of 308 km per day because the battery capacity is not sufficient for that. This illustrates the fact that type (1) long-range buses are less flexible in terms of operation and not as suitable for heavy duty operation sequences and highest utilisation. The effect from vehicle depreciation time, as shown in Figure 6, is slightly stronger for the electric buses because of the higher share of vehicle cost in the cost structure. The baseline analysis assumes the same service lives for conventional and electric buses. However, because of the ease to replace the traction battery at the end of battery lifetime, the service life of an electric bus may be longer than that of a conventional bus. If this is the case, the electric bus will gain some competitive advantage.

Figures 7 and 8 show that the sensitivity of the battery-related factors (price and cycle lifetime) is much more pronounced for type (1) long-range eBus than for the short-range type (2). This is because relative contribution to the total cost is greater in the long-range type (1) bus. It can also be noticed that the sensitivity of battery price, lifetime and also electricity price are largely equal between the type (2) short-range buses with either LTO or LFP batteries. For bus type (2), each of the sensitivity parameters in Figures 6 to 8 gives a variation in the operation cost of less than 0.1 €/km. Regarding energy consumption, it is clear that both energy efficiency of the vehicle with its auxiliaries and total energy management of the vehicles and fleet (Figure 4, eBus 2 LTO variants) can have a clear effect on total economy. Reduction in vehicle energy consumption kWh/km reflects directly in the operating range. Additionally, the price of electricity (see Figure 9) affects the TCO as shown in Figure 9.

The current analysis was carried out using a fleet of ten buses sharing the investment cost of the stationary charging infrastructure. If the charger could support more than the assumed amount of buses, consequently the charging infrastructure cost per bus would be smaller. The residual value of all battery systems and electric buses treated in this analysis was zero. In actual fact, certain battery chemistries may be useful for so called 2<sup>nd</sup> life applications. This would have the effect of reducing the battery and thus vehicle cost to some extent, but not more than roughly 0.1 €/km and depending on the residual value.

## VI. SUMMARY AND CONCLUSIONS

The present analysis supports the view that fully electric city buses do have the prospect of decreasing the carbon footprint, local emissions, and noise of public city transport. With significantly reduced operating costs due to high efficiency of the electric powertrains, the total cost of ownership of a fully electric city bus can be lower than conventional diesel bus. Vehicle technology, charging infrastructure and system level concepts have to be considered together for obtaining cost savings. The TCO model described in this paper combines all of these into a single model.

Consequently, it can be used in finding economical solutions for fully electric bus introduction into the transport system. The model indicates that short-range fully electric buses with shared opportunity charging infrastructure are the most economical solution.

The sensitivity analysis shows that no obvious show-stoppers were identified. If favourable parameter combinations can be reached through careful systems engineering and technological choices, the potential for TCO reduction by introducing electric bus systems is considerable. Care must, however, be exercised in making statements about the economy; each use case or electrification study needs to start with a proper look at the system level. Ambitious city and PTA strategies are needed to get started with this revolutionary change in public transport. Research can continue to support this transformation in taking into account the complex relationships in public transport in order to make fully electric city bus transport a sustainable reality. Such a transformation necessitates changes in the value chain of public transport with considerations of new business models, charging infrastructure ownerships, new traffic system designs, and operations.

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