ANALYSIS OF CO_2 EMISSIONS AND TECHNO-ECONOMIC FEASIBILITY OF AN ELECTRIC COMMERCIAL VEHICLE

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ABSTRACT

In order to attain emissions reduction targets to improve air quality and reduce global warming, electric vehicles (EVs) arise as alternatives to conventional vehicles fueled by fossil fuels. In this context, this work presents a comparative study between an EV and its conventional version, a medium-duty, diesel engine powered vehicle, from road tests following a standard cycle in urban driving conditions. The performance parameters evaluated are EV electric energy consumption and carbon dioxide (CO_2) emissions from electricity generation and, for the conventional vehicle, exhaust CO_2 emissions and energy consumption calculated from fuel consumption and heating value. Five scenarios were built to conduct an economic viability study in terms of payback and net present value (NPV). Considering the conditions applied, the results from the environmental analysis showed that CO_2 emissions from the EV was 4.6 times lower in comparison with the diesel vehicle. On the other hand, the economic analysis revealed that the viability of the EV is compromised, mainly due to the imported parts with unfavorably high exchange rates. In the best scenario and not considering revenue from commercial application, the calculated payback period of the EV is 13 years of operation.

Keywords: electric vehicle; CO_2 emission; fuel consumption; economic viability.

1. INTRODUCTION

The balance between the use of energy and the environment and issues related to global warming and air pollution are main requirements to the transportation sector. Thus, vehicle manufacturers are kept under pressure to develop cleaner propulsion systems and more efficient technologies. In this context, vehicles that use alternative fuels and electric vehicles (EVs) are in the focus in recent years. The International Energy Agency (IEA) sets policies to decrease equivalent carbon dioxide (CO_{2eq}) emissions and many countries adopted the introduction of EVs in the market as an important goal [1]. In 2009, for example, the German government set the goal of one million EVs on the streets by 2020, but until 2014 the units of pure electric vehicles were about 19,000 plus 33,000 hybrid vehicles. Thus, the government has introduced some incentives for the purchase of EVs, such as tax exemption, free parking and subsidies at the time of vehicle acquisition, among others [2].

An important aspect to take into consideration is that EVs can serve as stored system for the power grid when used in the vehicle to grid (V2G) mode, create monetary savings opportunities and minimize negative environmental impacts of both the energy and transportation sector [3]. Despite the many benefits of V2G, it has a negative impact on battery degradation, which is very sensitive to charging times and energy throughput. The application of V2G contributes to increase the frequency of battery replacement [4]. Another point to be considered is that the increased number of EVs on the streets may cause problems in the power system, such as peak loads, losses and congestion. Some authors have been studying charging strategies such as modeling the demand dispatch calculation [5], allocation of EVs parking lots [6], demand forecast in parking lots [7] and simultaneous allocation of distributed renewable resources and EVs in parking lots [8].

Many studies focus on the evolution of the EV market in different regions and countries, such as USA [3], Iceland [9], Canada [10] and Netherlands [11]. The evolution of EVs participation in the Nordic market during the period from 2012 to 2013 was determined using statistics methods to evaluate the purchase probability of an electric vehicle in different socioeconomic types [3]. The results showed that the decisive factors were the evolution of fuel and EV prices and government incentives. In an adverse scenario (low cost of fuel and high EV price), the introduction of EVs in the market would be possible only with tax exemption. In the Netherlands, the relationship between several factors and the adoption of 30 shared EVs was studied [11]. The developed model showed that financial incentives and recharge infrastructure are decisive factors for the adoption of EVs, but none of the factors studied can guarantee increased EV sales.

Besides the economic factor, the social factor is decisive in the expansion of EVs [12]. The willingness to explore a new product and a new technology depends on customer stability and lifestyle. The consumer preference for environmentally and emerging technologies are not pre-formed and static, but dynamic built through knowledge and exposure in social interactions.

The evolution of EVs market share also raises considerations about the impacts on grid distribution. For the Netherlands it was projected that an increase of 30% of EVs fleet can increase the national grid peak load by 7% and household peak load by 54% [13]. In Italy, the charging demand is increasing between 6-12 a.m. when the users reach the job and plug the vehicle into the grid for charging [14]. In Brazil, it was reported that an introduction of 10% of EVs in the fleet can increase by 2% the electricity demand [8].

On the other hand, there can be electricity waste if it is not stored when the demand is lower than the current electricity level [3]. When operating in a V2G system, EVs have the capability to be used as energy storage system feeding back to the grid the idle energy of their traction batteries [16-19]. Thus, EVs deployment poses both a challenge and an opportunity for the operation of power grids Daina et al. [20]. A way to overcome the grid peak load is charging the vehicle at off-peak hours, although some studies point out that this practice has the drawback of higher emissions factor when power generation is not from renewable sources [14,21,22]. Nevertheless, in a scenario with power generation by natural gas, off-peak charging pattern results in 8% reduction in greenhouse gas (GHG) emissions if compared to uncoordinated charging [13].

Power generation mix is the major factor to take into account in EV's emissions factor calculations. EVs emission is strongly dependent on the time of the day the vehicle is charged because of variation in the power generation mix [14]. In Germany, the influence of EV charging on the specific CO_2 emission factor was analyzed for the period between 2020 and 2030, with no additional renewable power generation capacities due to EV fleet market share increase [21]. It was concluded that EV charging electricity factor is bigger than overall power consumption emission factor. Also in Germany, considering power generation from renewable sources, EV emissions were found to be 62-64% lower than conventional vehicles [23]. It was also concluded that EV emissions is lower than conventional vehicles only with annual driving distances higher than 4000 km for German current grid mix.

The maximum CO_{2eq} emissions from electric power generation to maintain the global warming potential (GWP) of EVs below the internal combustion engine vehicles was calculated for the electric matrices of several European countries and 6 driving cycles [24]. The Monte Carlo simulation applied also analyzed some vehicular characteristics, such as mass, drag coefficient, efficiency and regenerative braking. The results showed that most of the countries analyzed have adequate electric matrices to accommodate the introduction of EVs in the market, which, in general, contribute to reduce greenhouse gas

(GHG) emissions. Despite most countries have taken steps to modify their fleet, some countries still have highly pollutant electricity matrix and require improvements to reduce CO_{2eq} emissions.

A survey in the Netherlands, in 2015, where most of power generation is from natural gas, showed that the emission from electric driving is between 35-77 gCO_{2eq} km^{-1} [13]. Charging EVs with electricity from natural gas instead of coal can reduce emissions down to 47 gCO_{2eq} km^{-1}. The replacement of diesel engine powered buses by electric ones can reduce around 60% of CO_{2eq} emissions in countries where electricity is generated from thermal and nuclear sources [25]. In Brazil, where electricity is mostly produced from hydroelectric power plants, an introduction of 10% of electric vehicles can reduce 1.3% of GHG emissions [15]. For a high carbon grid comprised of 7% zero-emission fuels, < 1% natural gas and 93% coal, EVs produces only slightly lower emissions than conventional vehicles [23]. In the U.S., the reduction of emissions factor from EVs fleet introduction is linked to V2G deployment [3]. From the analysis of different regions across the U.S., it was concluded that V2G technologies can achieve significant emissions reduction even with high level of battery degradation.

The reductions in energy use and CO_2 emissions from the introduction of electric buses in China's transportation sector was studied using a lifecycle analysis (LCA) [26]. Three operating systems were used in Macao considering the use of air conditioning, load and speed. In the minimum load scenario, buses with 12 m length reached between 138 and 175 kW.h/100 km, while buses with 8 m length reached 79 kW.h/100 km. When air conditioning and load were at their maximum values, energy consumption was increased in the range from 21% to 27%. The use of air conditioning showed a higher impact than passenger load. The performance of the diesel engine powered buses on the road was superior to the electric powered buses at low speeds, high load and using air conditioning.

From the life cycle analysis, electric buses reduce the use of fossil fuels from 32% to 46% and CO_2 emissions from 19% to 35%, in comparison with diesel buses. A cleaner power grid and an increased system recharge efficiency (over 60%) would increase the future benefits of electric buses.

Well-to-wheel GHG emissions, energy consumption and other pollutants were compared for four different technologies – hybrids, hybrids plug-in, electric and conventional vehicles – using data from Beijing in 2015 and a prediction to 2030 [27]. The LCA was performed, and a sensitive analysis was used to evaluate the key parameters. The results showed that hybrid plug-in vehicles and battery powered EVs could reduce CO_2 emissions by 46% and 32%, respectively. The results also indicated that EVs can reduce emissions of volatile organic compounds (VOC) and oxides of nitrogen (NO_X) if the power plants adopt the selective catalytic reduction by 2030.

The energy matrix composition is not the only factor that influence GHG emissions reduction from the insertion of EVs in the fleet. It was found that charging workplace availability results in lower electric vehicles emissions [22], and, in Germany, emissions of EVs are higher than conventional vehicles in the production phase [23]. Hence, a complete analysis of emissions from fuel/electricity production, transportation, distribution and operation is necessary for each country or region. From a lifecycle comparison of an EV and a conventional vehicle considering the same travel distance, it was found that the production parts (except engine and battery), transportation and disposal can be disregarded in the calculation of total energy consumption and CO_{2eq} emissions, since these parameters are concentrated in the operation phase [28]. GHG mitigation from changing the current vehicle fleet by EVs in Canada ranges from 4.3 to 5.1 $kgCO_{2eq}$/year/vehicle [10]. This analysis only considered emissions from EV operation.

The high cost of traction batteries is one of the main barriers to large-scale EVs production. Battery EVs are not cost-competitive with hybrid vehicles (HEVs) and conventional vehicles unless battery costs reach € 150 kW.h^{-1} [13]. The IEA estimates that the traction battery price should be less than € 200 kW.h^{-1} to turn the EV price competitive [1]. The cost of the traction battery in the period from 2010 to 2013 was reduced by around 50%. According to IEA estimates, keeping this trend the cost of traction battery will reach competitive levels before 2020. Battery price evolution scenario is € 275 kW.h^{-1} by 2020 and € 180 kW.h^{-1} by 2030 [23]. A previous report states that EVs equipped with Zebra batteries will be economically competitive compared to diesel vehicles only if the battery charge reaches € 66.3 kW.h^{-1} and an autonomy larger than 200 km/day [29].

Battery and charging station lifetimes have low influence on EV charging costs [10]. Therefore, using high-cost fast charging infrastructure to reduce EV charging time can increase charging costs by 11% in a case scenario of hydro energy power system and average travel distance of 65 km. Some parameters such as travel distance, fuel economy/price, EV price and depreciation are the most important for EVs economic feasibility studies [30].

An evaluation of the payback and net present value (NPV) of light commercial EVs for different use profiles showed them economically feasible for travels longer than 96.5 km/day [16]. The study concluded that there is an increase in the NPV when EVs are used in V2G with power loading of 19.2 kW and electricity price of € 14.6 MWh^{-1}. Comparing an electric school bus operating in V2G to the diesel version, an U.S. study concluded that the electric version saved € 4,161 per seat in a year [18]. This value could be around € 27.74 million with replacement of the whole fleet. An electric delivery truck running in New York was found to have a total cost ownership 22% lower than the diesel version [17]. Battery EVs connected to a V2G system can produce a net revenue of € 40,000 per vehicle in the U.S. [3]. However, the viability of using V2G technology is directly related to market aspects of energy trades [19].

Many studies evaluate EVs cost-emission using virtual models, therefore, more studies that use real EV data are required [23]. EV consumers are recommended to use their regional grid emissions as a guide to estimate EV global warming emissions due to variation of emissions intensity across the regions. Appropriate models for planning electricity generation capacity and CO_2 emissions from EVs consider specific emission factors for electricity generation and, thus, it should be done on a regional basis [20]. In this context, the aim of this paper is to evaluate the economics and the potential to reduce CO_2 emissions of a typical medium duty urban EV, by comparison with a similar conventional diesel model using an on-the-road back-to-back methodology.

The main novelty of this paper is to present an analysis and results based on a distinct electric matrix, where renewable sources account for 82.4%: 68.9% hydroelectric, 8.7% biomass and 4.8% wind [31]. This study was based on the Brazilian electricity matrix, where the participation of renewables was increased by 6.9% from 2015 to 2016 [31]. Regional aspects, such as economy, driving profile and fuel/electricity prices, were taken into account, but the results are expected to be equally useful to model estimate studies based on regions and countries with less participation of renewables for electricity generation. A schematic overview of the paper structure is shown by Fig. 1.

2. METHODOLOGY

2.1 Experimental procedure

This work compares two different minibuses used for passenger transportation: an IVECO DAILY 55C17 Diesel and a 100% electric IVECO DAILY 55 C/E. Information about the vehicles, battery and engine are shown by Tabs. 1 to 3. Vehicle speed, position and time were recorded by a GPS Racelogic® VBOX data acquisition system, and diesel fuel consumption was measured by an AIC® 4004 VERITAS flowmeter. Fuel consumption was verified through a board computer BC 3034. The adopted procedures were based on SAE J1264 [32] and SAE J1321 [33] standards. The tests occurred in a 17 km urban route.

Both the conventional and the electric vehicle had similar tires, size and pressure. The vehicles were clean, free of faults and also had no missing parts. The electric loads in both vehicles remained fairly constant throughout the tests. The axle loads were reasonably close in both vehicles, reaching the total weight of 5,300 kg. After each test, the drivers were interviewed about the driving mode and, if any discrepancy was found during the test, the data was discarded and the test was repeated after correcting the problem.

Also, after each test, the drivers changed to the other vehicle in order to eliminate variability from driving mode. In addition, the electric vehicle always started the test 5 minutes before the diesel engine powered vehicle, avoiding driving mode influences. A total number of six tests were performed along three days to produce the average data of torque, power, battery charge condition, fuel consumption, time and distance traveled by both vehicles shown later in the results section.

2.2 Economic analysis

The electric vehicle used in this work was constructed based on the diesel version, removing the internal combustion engine, transmission, cardan shaft, exhaust system and fuel. Other components were added, such as the traction battery, invertor and electric engine. All electric parts were imported, increasing the final price of the electric vehicle to around four times that of the diesel version. In a scenario with governmental incentives, the electric vehicle price could reach around 2.8 times the price of the diesel version. The annual depreciation was considered the same for both vehicles, since the conditions of use and distance are the same.

The maintenance cost was based on the owner’s manual. The brake pads of the electric version can last two times more than the Diesel version due to regenerative braking. Besides, the electric version has fewer rotating parts, which contribute to reduction of the maintenance components. However, the electric vehicle has many imported parts, which increase the final cost. The adopted exchange tax (TCer) was the average appreciation of the Euro against the Brazilian currency Real in 2015. The government incentive was the tax-free for imported products. The inflation tax (Tinf) was the average of Price Index Broad Consumer.

Considering TR_{km} the distance for the change of the maintenance item j (km) and QA the annual distance traveled by the vehicles (km), the annual frequency of change (FTj) can be calculated by:

The annual maintenance cost of the diesel vehicle ($Cman_d$) is calculated by:

Where y is the year; Q_j is the quantity of maintenance item j in the year y; CU_j is the unitary cost of the maintenance item j in 2015.

The annual maintenance cost of the electric vehicle ($Cman_e$) is expressed by:

Where Q_{jimp} is the quantity of imported maintenance item (jimp) in the year y; CU_{jimp} is the unitary cost of maintenance of imported item (jimp), which was considered constant over the years.

The annual cost of the energy consumption of the Diesel vehicle is calculated by:

Where $Pefc_d$ is the diesel vehicle efficiency (km/l); $Ccbs_{d,0}$ is the initial fuel price (EUR 1.061/L); $Tinf_d$ is the annual inflation rate of the fuel (5.96%).

The annual cost of energy consumption ($Ccbs_e$) of the electric vehicle depends on the energy prices in 2015 ($Ccbs_{e,0}$), taken as 0.2896 EUR/kW.h, the annual traveled distance QA (km), the efficiency $Pefc_e$ (kW.h/km) and the inflation rate $Tinf_e$:

The cost of the recharge station Ccel, of EUR, was considered constant during its life cycle and the type was 15 kW level II, with recharge time of 8 hours and the total cost was EUR 767.83. The cost of the traction battery (Cbtv) was considered EUR 1.018/kW.h, using the exchange rates of 2.7467 for EUR/R$ and 2.2671 US$/R$.

The economic feasibility of the replacement of the diesel powered vehicle by the electric vehicle could be analyzed according to the net present value, which is the difference between the invested value and the amount recovered at the end of the investment. All the cash flow over the years are transformed into current monetary values through an annual return rate (TR). In this case, the annual cash flow is represented by the difference between the total cost of ownership of the diesel vehicle ($TCO_{d,y}$) and the electric vehicle ($TCO_{e,y}$). The total cost of ownership is composed by $Cman_d$, $Cman_e$, $Ccbs_d$ and $Ccbs_e$. The total investment is the difference between the electric vehicle ($Ccom_e$) and recharging equipment price (Ccel) and the diesel vehicle price ($Ccom_d$). The general equation is:

2.3 Environmental analysis

This section describes the calculation of CO_{2eq} emissions for both vehicles using the well-to-wheel methodology. The data from Macedo et al. [34] are used to calculate the CO_{2eq} emissions for the diesel vehicle in the phase well-to-tank, which was 0.137 $kgCO_{2eq}/l$. To calculate the emissions in the tank-to-wheel phase, CO_{2eq} emissions data from tests conducted with a FPT F1C model engine in the ESC (European Stationary

Cycle) test schedule composed by 13 mode cycle were adopted. The tests were conducted based on the Brazilian standard ABNT NBR 15634 [35]. The results showed the concentration of the pollutants (CO, NOx, CO_2 and HC) on wet basis (% v/v), which were then converted to pollutant mass flowrate (g/h) based on ABNT NBR 14489 [36] standard:

Where i is the mode cycle; NO_{Xi} is NO_X emissions (g/h); HC_i is HC emissions (g/h); $CO_{2\,i}$ is CO_2 emissions (g/h); m_{ei} is the exhaust gas flowrate (kg/h).

The exhaust gas flowrate m_{ei} is calculated by:

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Where F/A_i is the fuel/air ratio; m_{ari} is the intake air mass flowrate (kg/h).

The specific emissions ($kgCO_{2eq}/l$) calculated based on ABNT NBR 15634 [35] standard are:

Where: $D_{(i)}$ is time (h); $FP_{(i)}$ is a correction factor; $m_{f(i)}$ is the diesel fuel mass flowrate (kg/h); ρ_{S10} is the diesel S10 density (kg/l); GWP_{NO2}, GWP_{CH4} and GWP_{CO2} are global warming potentials.

The general equation for the well-to-wheel CO_{2eq} emissions for the diesel vehicle ($PRCO_{2eq}$) is:

The well-to-tank emissions of the electric vehicle are composed by the electricity production, transmission and recharge point. The tank-to-wheel emissions is taken as zero. The manufacture and disposal of the ZEBRA battery is here considered. The annual emissions from the electricity production to supply the electric vehicle is:

Where EF_e is the electricity transmission efficiency (%); FEP_{ee} is the emission factor to produce electricity ($kgCO_{2eq}$/kW.h); QA is the annual travel distance.

The data from Longo et al. [37] was used to calculate the emissions of the manufacture and disposal of the Zebra battery. The general equation of the electric vehicle annual emissions (EVECO$_{2eq}$) is:

3. RESULTS

The electric vehicle speed profile obtained from the average of six tests is shown by Fig. 2. The speed profile is typical from traffic of urban areas with constant stop and go. Between the 8 km and 10 km the vehicle operates in the city center, with a heavy traffic condition. The energy consumption in this region was up to 0.6 kW.h/km and, and the speed ranged between 25 km/h and 30 km/h. Some intervals had zero energy consumption due to the existence of slopes, where the regenerative brake works. The region between 11 km and 12 km had a moderate slope and free traffic, which contributes to high speed and energy consumption up to 0.7 kW.h/km. This consumption could be explained by the increase of air resistance in this area. However, in general, the electric vehicle energy consumption peaks ranged between 0.60 kW.h and 0.65 kW.h, and the vehicle speed ranged between 45 km/h and 50 km/h. The average speed and energy consumption of the EV was 21.54 km/h and 0.408 kW.h, respectively. With regard to the conventional vehicle, the average fuel consumption was 7.487 km/l, corresponding to 1.3 kW.h/km, considering the diesel lower heating value as 42.7 MJ/kg. Considering that the travel distance was 17 km, the average fuel energy consumption was 22.01 kW.h ± 0.56

kW.h. Thus, the conventional diesel vehicle would have to be around 2 times more efficient to match the electric vehicle efficiency.

Figure 3 shows that the energy consumption of the electric vehicle over the distance travelled indicates a linear relationship. Figure 4 shows that the EV motor operated below the rated power (40 kW), but the rated torque (120 Nm) was exceeded many times. It is possible to note the ability of the electric engine to achieve high torque in a short time. It is also observed that the electric motor reached about double the rated torque during start up.

The results about the economic analysis were divided in five scenarios, which features are shown by Tab. 4. Fig. 5 presents the total cost of ownership of the electric and conventional diesel vehicles for 15 years of operation. The cost of the electric vehicle is 2.5 times higher than the Diesel version, wherein the cost of the traction battery and the sales price of the vehicle were the most important factors to show this difference. The operation cost of the Diesel vehicle was higher than the electric vehicle, as expected, since the cost of electricity is lower than the fuel cost. A larger difference of the maintenance cost between the vehicles could be expected, but it was not verified due to the battery and other components of the electric vehicle be imported, contributing to the reduction of the difference of maintenance costs.

Under the conditions established in the baseline condition, Fig. 6 shows that the EV is not economically feasibility without considering the revenue from commercial utilization [38]. The NPV is always lower than zero, decreasing every year and closes with the negative value of EUR -212,634.10. The increase in TCO of the electric vehicle in 5, 10 and 15 years corresponds to the change of the traction battery pack in these periods. Figure 7 presents a sensitivity study of many parameters that influence the NPV, considering the baseline case. The traction battery cost and the exchange rate are the most significant variables, followed by the import cost and investment return. The oscillation in fuel/electricity prices and the distance traveled have less influence in the net present value.

The results from the four scenarios studied are presented in Fig. 8. In scenario I, the parameters considered were: initial diesel and electricity prices in 2015, annual inflation diesel/electricity rate, zero import cost, decreasing exchange rate and traction battery/other components. Economic feasibility is observed for the battery cost (EUR 43.87/kW.h) and exchange rate (R$0.80/EUR). The diesel vehicle TCO is higher from the 8th year, and the payback occurs only in the 12th year. The final profit was around EUR 8,191.65. In scenario II, the initial Diesel and electricity prices in 2015, decreasing annual inflation electricity rate and traction battery cost, increasing annual inflation fuel rate, and zero import cost were considered. In this case, there is no economic feasibility. Only if the other components and the traction battery had zero import costs and a favorable scenario with high diesel fuel costs and low electricity cost was available, the technology would be feasible.

In scenario III, the considerations were: initial electricity and diesel prices in 2015, annual inflation electricity/diesel rate, decreasing traction battery cost, battery and other equipment nationalized. Figure 8 shows an economic feasibility for this scenario when the battery cost is around EUR 10.92/kW.h. The diesel vehicle TCO is higher from the 6th year, and the payback occurs in the 9th year. The final profit for the period is EUR 15,787.32. In scenario IV, the considerations were similar to scenario III, except for the inflation rate of electricity, which was considered decreasing, and the inflation rate of fuel, which was considered increasing. It is possible to note the economic feasibility when the traction battery cost is around EUR 87.38/kW.h, considering the annual inflation rate of fuel and electricity as 9.54% and 1.94%, respectively. The diesel vehicle TCO is higher from the 8th year, and the payback occurs in the 13th year. The final profit for the period is EUR 9,110.96.

Considering the scenarios analyzed, the results show economic feasibility of the electric vehicle for traction battery prices below the suggested viable price by Van Vliet et al. [6], of EUR 150.00/kW.h, and IEA (2013), of EUR 246.84/kW.h. In Scenario IV, the traction battery price was close to the value of EUR 82.64/kW.h proposed by Gerssen-Gondelach and Faaij [29], but with a reduction in the annual inflation rate of electricity unlikely to be reached in the current Brazilian economic scenario. For the baseline case, the total cost of ownership of the electric vehicle is about 60% higher than the diesel version, much higher than the 22% of the study presented by Lee et al. [17]. This is due to the import and exchange costs, which were taken into account in the baseline case study, since the components and electric vehicle parts are currently imported from Europe. Scenario II shows that, for the current exchange rate situation, even with the tax-free and conditions for adoption of the electric vehicle, high diesel oil prices and low electricity price, the electric vehicle is not feasible compared to the diesel version. Considering the viable scenarios, the payback was over 9 years, while Davis et al. [39] point out 8 years. This is due to the larger difference between the diesel oil and electricity prices in other studies. In this work, the diesel oil price is only 3 times the price of electricity. Table 5 shows a summary of the scenarios adopted and the results obtained.

Figure 9 presents the results of total CO_{2eq} emissions for both vehicles. The emissions from the diesel vehicle are 4.6 times higher than the electric version. Operation of the diesel vehicle is responsible for 97.3% of the total CO_2 emitted, closely resembling the results presented by Aguirre et al. [28], of 96%. CO_2 emissions from electricity generation and transmission is 3.5 times higher than diesel fuel production and transportation. The production and disposal of the traction battery are responsible for most of the electric vehicle CO_2 emissions, representing 55.8% of the total, which confirms the results obtained by Lee et al. [17]. In summary, these results show that, while for the conventional vehicle CO_2 emissions can be mitigated through attainment of reduced fuel consumption and use of renewable fuels, especially carbon-free fuels, for the EV energy generation/transmission and battery production/disposal affect CO_2 emissions in the same magnitude. Thus, CO_2 reduction from EVs can be attained by both using renewable energy sources for electricity generation and increasing the battery lifecycle.

High level of CO_2 emissions during electricity generation and transmission, compared with diesel oil, can be explained by the emission factor from the Brazilian electric matrix due to the increase of thermal power generation. Figure 10 shows the relation between the emission factor and the difference on CO_2 emissions from the diesel and electric vehicles. If the emission factor from the electric matrix exceeds 1.05 $kgCO_{2eq}/kW.h$, a value nearly 13 times higher than the 2016 average value, of 0.0817 [40], the electric vehicle will pollute more than the diesel version. This value is higher than the results from Prud'Homme and Koning [41], of 0.650 $kgCO_{2eq}/kW.h$. However, the authors considered the same efficiency per unit kilometer traveled and, in the region of studied, power generation is thermal and nuclear based. If the same procedure could be used in this work, a value lower than 1.05 $kgCO_{2eq}\ kW.h^{-1}$ could be found.

Figure 11 presents a sensitivity analysis for the difference in CO_2 emissions from the vehicles. Some parameters such as the emission factor of the traction battery, diesel oil production and transport, electric vehicle efficiency and oscillations in emission factor from the electric matrix have low influence on the emissions difference. The traveled distance and diesel vehicle efficiency have higher influence on the difference of CO_2 emissions. The difference in CO_2 emissions is proportional to the annual distance traveled, so the use of an electric vehicle with higher autonomy will contribute to increase the difference. Thus, while increased diesel fuel conversion efficiency is the key parameter do improve CO_2 emissions from the conventional vehicle, recent developments on battery to increase EV autonomy simultaneously contributes to CO_2 emissions reduction.

The results here presented are expected to provide further data for estimates of CO_2 emissions from the replacement of conventional vehicles by EVs, considering an electricity matrix highly based on renewable sources. It also provides valuable information on economic analysis and feasibility studies, which can help to drive government policies to stimulate large scale adoption of EVs.

5. CONCLUSION

From the results obtained, the following conclusions can be drawn:

- The total cost of ownership of the electric vehicles is 2.5 times higher than the conventional vehicle, having the purchase price and the battery price as major costs.
- Under the current economic scenario take as baseline condition for this investigation, the feasibility of EVs can only be attained through government incentives or considering revenue from commercial activity.
- In the best scenario considered in this study, the payback of the EV would only occur after 13 years of operation.
- The EV emitted lower amounts of CO_{2eq} from electricity generation than the diesel vehicle exhaust, even in a scenario of high emission factor.
- For the baseline conditions considered, CO_{2eq} emissions from the EV was 4.6 lower than the conventional vehicle.

- Electricity generation/transmission and battery production/disposal affect CO_2 emissions from electric vehicles with close magnitude.
- Increased vehicle autonomy, increased battery lifecycle and use of renewable energy source for electricity generation can improve even further the advantages of EVs over conventional vehicles regarding CO_2 emissions.

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8. NOMENCLATURE

Cbtv – traction battery cost (R$/kW.h)

$Ccbs_e$ – annual energy cost (R$)

$Ccbs_{d,0}$ – initial Diesel cost (R$/l)

$Ccbs_e$ – annual electricity consumption cost (R$)

$Ccbs_{e,0}$ – initial electricity cost (R$/kW.h)

Ccel – cost of recharging station (R$)

Ccom – purchase cost (R$)

$Cman_d$ – annual Diesel vehicle maintenance cost (R$)

$Cman_e$ – annual electric vehicle maintenance cost (R$)

$CO_{2(i)}$ – CO_2 emission (g/h)

CO_{2eq} – the equivalent carbon dioxide (kg)

CU_j – Unit cost of maintenance (R$)

CU_{jimp} – Unit cost of import maintenance (€)

EF_e – efficiency in electricity transmission (%)

$F/A_{(i)}$ – ratio fuel/air (-)

FEP_{ee} – emission factor from electricity production ($kgCO_{2eq}$/kW.h)

$FP_{(i)}$ – corrector factor (-)

FT_j – exchange frequency (-)

GWP_{CH4} – Global warming potential of CH4 (-)

GWP_{CO2} – Global warming potential of CO_2 (-)

GWP_{NO2} – Global warming potential of NO_2 (-)

$HC_{(i)}$ – HC emissions (g/h)

i – test mode number (-)

j – maintenance item (-)

y – year (-)

$m_{e(i)}$ – exhaust gas flow (kg/h)

$m_{f(i)}$ – fuel flow (kg/h)

$NO_{X(i)}$ - NOx emissions (g/h)

$PBTCO_{2eq}$ - annual emissions due to production/disposal traction battery ($kgCO_{2eq}$)

$PEECO_2eq$ – annual emissions due to electricity consumption ($kgCO_{2eq}$)

$Pefc_d$ – diesel vehicle efficiency (km/l)

$Pefc_e$ – electric vehicle efficiency (kW.h/km)

$PRCO_{2eq}$ – emission well-to-wheel of the Diesel vehicle ($kgCO_{2eq}$)

$PTCO_{2eq}$ – emission well-to-tank of the Diesel vehicle ($kgCO_{2eq}$/l)

QA – annual distance traveled (km)

Qj – quantity of maintenance item j (-)

Qjimp - quantity maintenance imported item (-)

TCer – exchange rate Real/Euro (R$/€)

$TCO_{d,y}$ – total cost of Diesel vehicle ownership (R$)

$TCO_{e,y}$ – total cost of electric vehicle ownership (R$)

Tinf – annual inflation rate (%)

$Tinf_d$ – annual Diesel inflation rate (%)

$Tinf_e$ – annual electricity inflation rate (%)

TR – annual return rate (%)

$TRCO_{2eq}$ – emission tank-to-wheel of the Diesel vehicle ($kgCO_{2eq}/l$)

TR_{km} – Distance required for the exchange of vehicle components (km)

ρ_{S10} – Diesel S10 density S10 (kg/l)

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Table 1 - Vehicle datasheet.

	IVECO DAILY MINIBUS	
Parameters	Diesel 55 C17	Electric 55 C/E
Length	7012 mm	7012 mm
External width	2025 mm	2025 mm
External height (empty)	2930 mm	2930 mm
Wheelbase	3950 mm	3950 mm
Total gross weight	5300 kg	5300 kg
Maximum power	125 kW	80 kW
Maximum torque	400 N.m	300 N.m
Seats	20	20
Doors	2	2
Transmission	Manual	N/A
Autonomy	N/D	100 km
Fuel tank	100 l	N/A
Battery	N/A	21.2 kW.h
Recharge time	N/A	8h
Grade ability	43%	18%
Tires	195/ 75R16	195/ 75R16

Table 2 - ZEBRA battery datasheet.

Parameter	Value
Capacity	76 A.h
Mass	182 kg
Energy	21.2 kW.h
Voltage	278 V
Specific energy	119 W.h/kg
Specific power	169 W/kg
Coolant	air
Maximum power	30 kW

Table 3 - Diesel engine and electric motor datasheet.

Parameter	Diesel engine	Electric engine
Model	FPT F1C DS	-
Number of cylinders	4	-
Total displacement	2998 cm^3	-
Bore × stroke	95.8 mm × 104 mm	-
Compression ratio	17.5 ± 0.5 :1	-
Rated power	-	40 kW
Weight	-	79.5 kg
Maximum power	125 kW @ 3500 rpm	-
Rated torque	-	120 N.m
Maximum torque	400 Nm @ 1300 - 2700 rpm	-

Table 4 - Scenarios evaluated in economic analysis.

Description	Base case	Scenario I	Scenario II	Scenario III	Scenario IV
Initial diesel fuel price (EUR/l)	1.06	1.06	1.06	1.06	1.06
Initial electricity price (EUR/kW.h)	0.29	0.29	0.29	0.29	0.29
Inflation rate y.y (%)	6.58	6.58	6.58	6.58	6.58
Diesel fuel inflation rate y.y (%)	5.96	5.96	↑	5.96	↑
Electricity inflation rate y.y (%)	4.86	4.86	↓	4.86	↓
Import costs (%)	45	0	0	0	0
Exchange rate (EUR/R$)	2.7467	↓	2.7467	0	0
Traction battery cost (EUR/kW.h)	1,017.76	↓	↓	↓	↓
Recharge station (EUR)	767.83	767.83	767.83	767.83	767.83
Electric vehicle price (EUR)	203,865	↓	↓	↓	↓
Diesel vehicle price (EUR)	51,698	51,698	51,698	51,698	51,698
Electric vehicle efficiency (kW.h/km)	0.480	0.480	0.480	0.480	0.480
Diesel vehicle efficiency (km/l)	7.487	7.487	7.487	7.487	7.487
Application rate y.y (%)	12	12	12	12	12

Legend: ↑ increase ↓ decrease

Table 5 – Summary of scenario results.

Scenario	Results
Base	– EV cost was 2.5 higher than the Diesel version due to decisive factors: traction battery and purchase cost of the vehicle – Diesel vehicle operation cost was higher than EV due to the low electricity cost compared to diesel fuel
I	– Economic feasibility is observed for battery cost around EUR 44/kW.h – TCO_{diesel} is higher from the 8th year – Payback: 12th year – Final profit: around EUR 8,192
II	– There is no economic feasibility in this scenario
III	– Economic feasibility is observed for battery cost around EUR 11/kW.h – TCO_{diesel} is higher from the 6th year – Payback: 9th year – Final profit: around EUR 15,788
IV	– Similar considerations as scenario III – Economic feasibility is observed for battery cost around EUR 88/kW.h – TCO_{diesel} is higher from the 8th year – Payback: 13th year – Final profit: around EUR 9,111

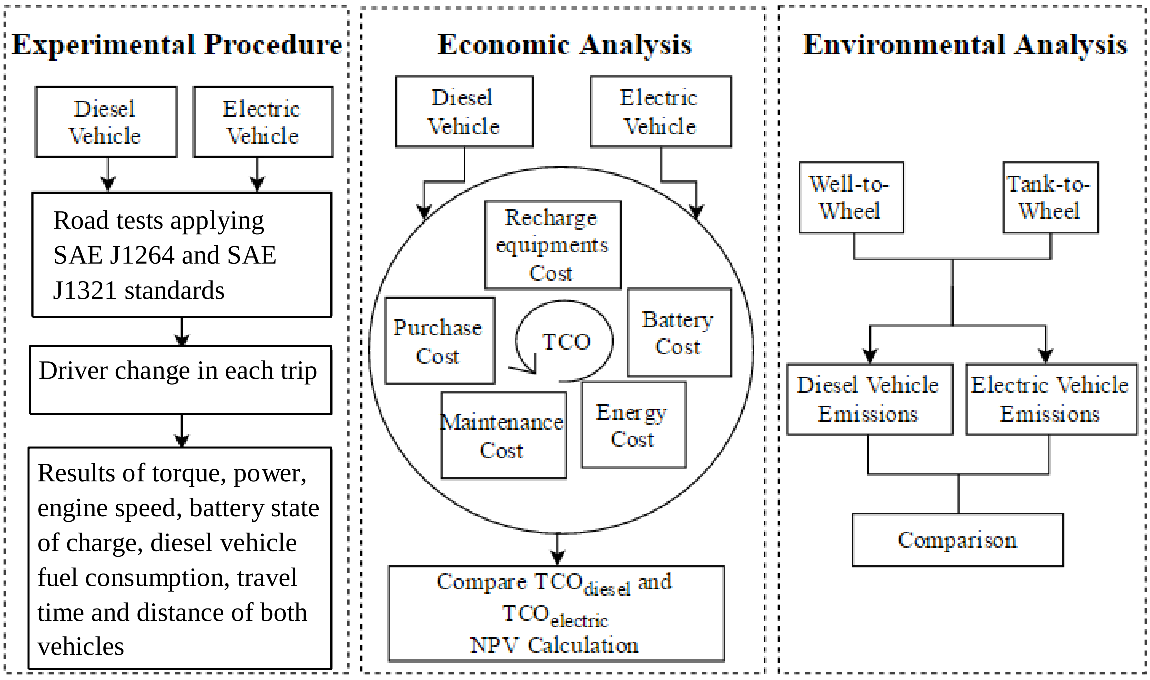


Figure 1 – Paper overview.

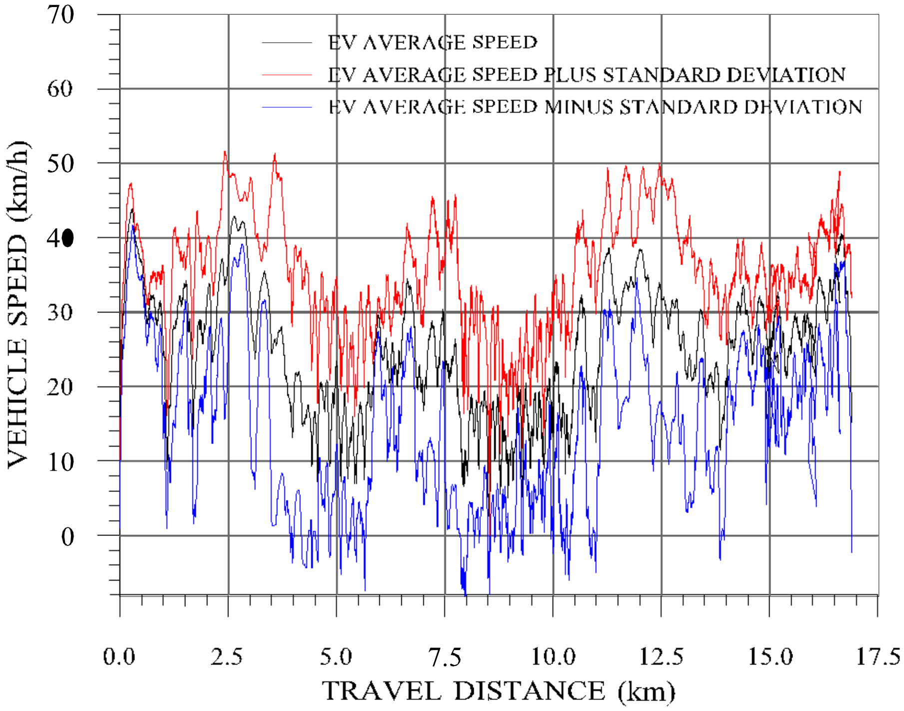


Figure 2 – Variation of electric vehicle speed with travel distance.

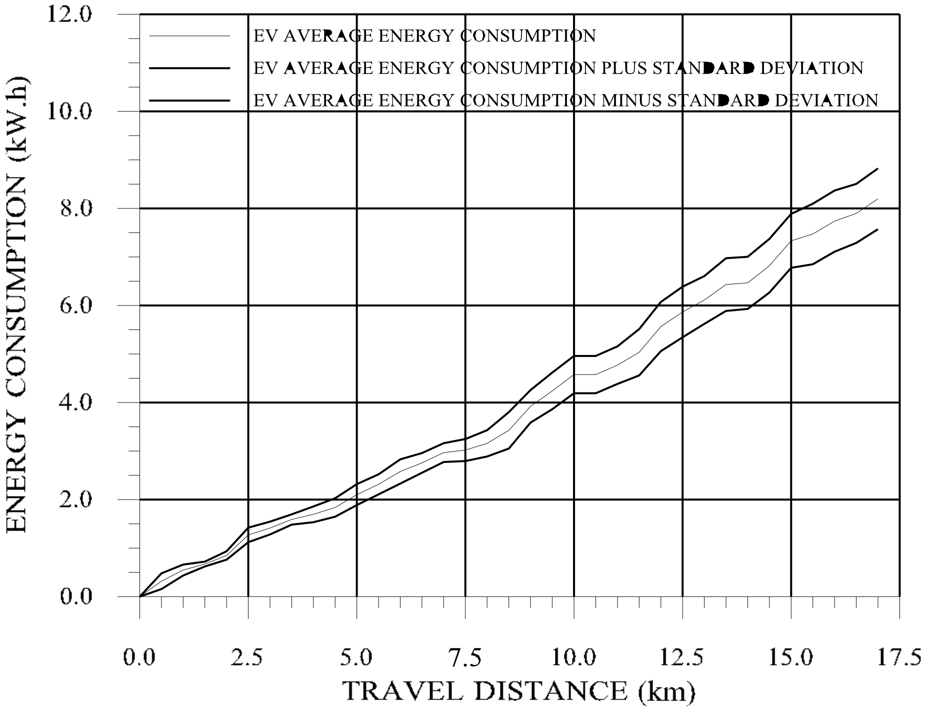
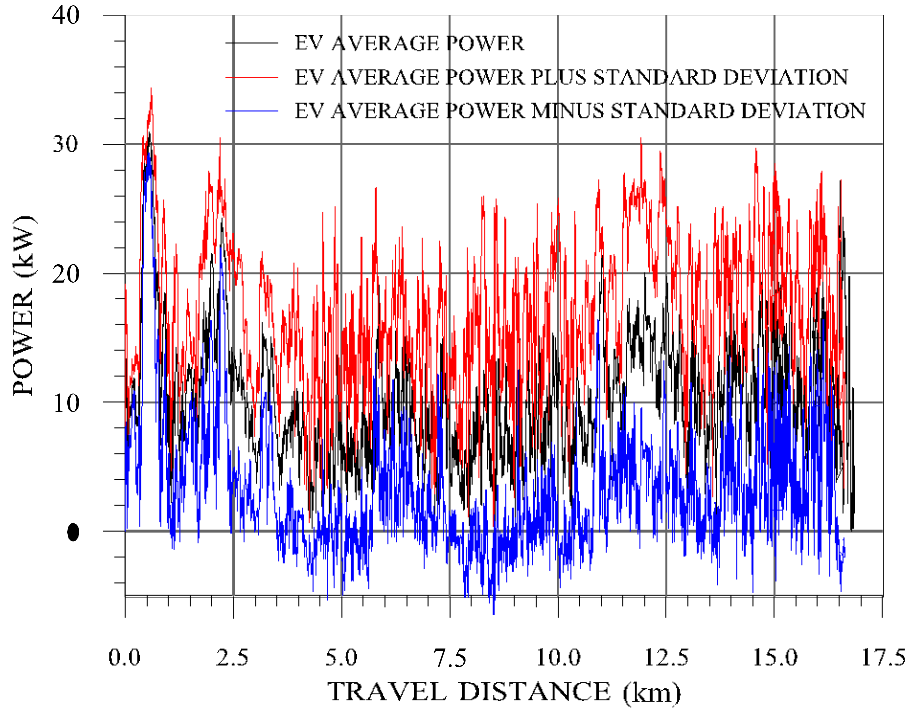


Figure 3 – Variation of electric vehicle energy consumption with travel distance.



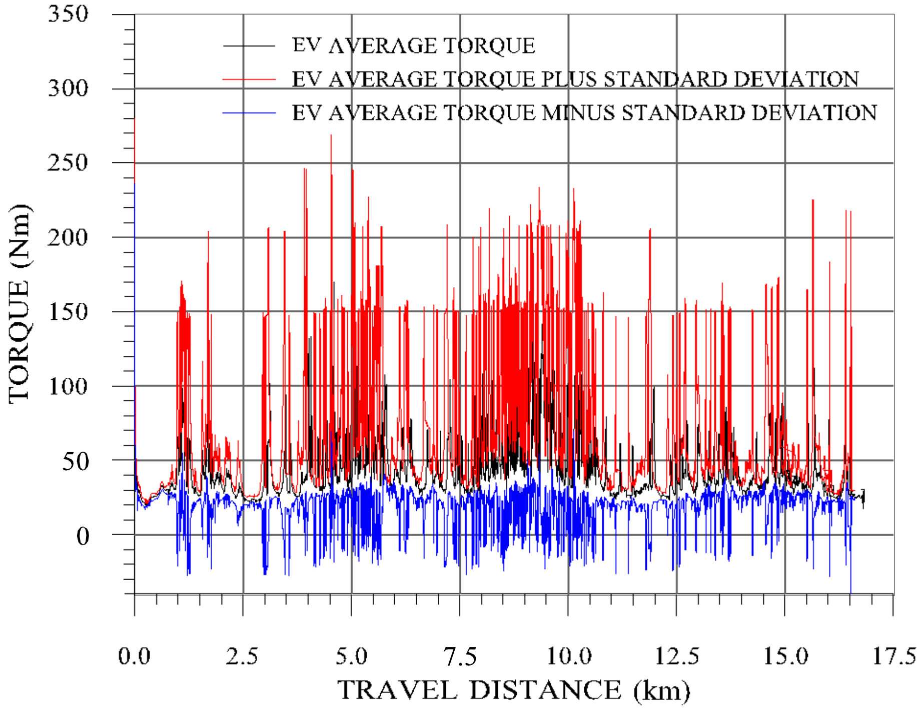


Figure 4 – Variation of electric vehicle power and torque with travel distance.

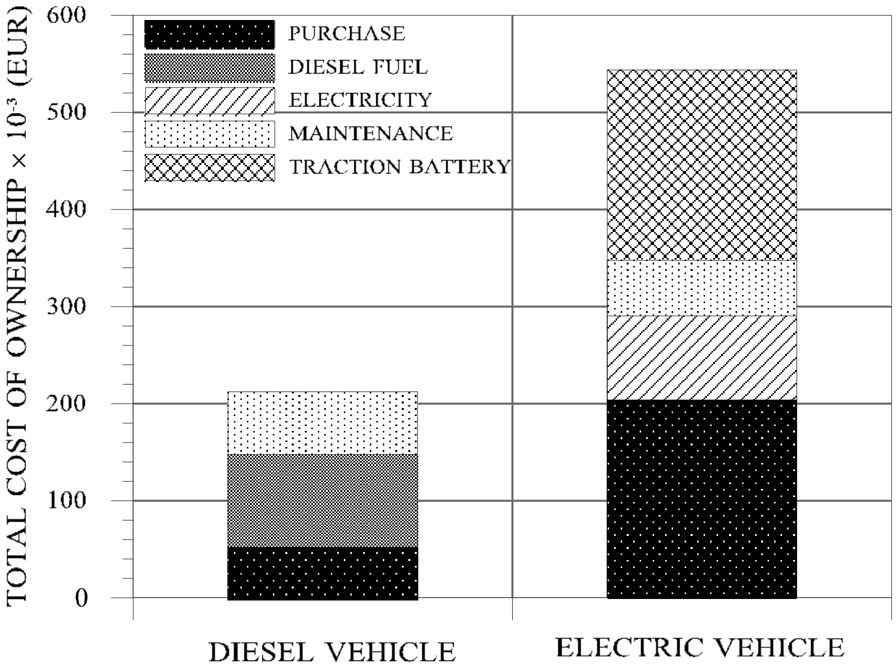


Figure 5 – Total cost of ownership (TCO) of the diesel and electric vehicles at the end of 15 years.

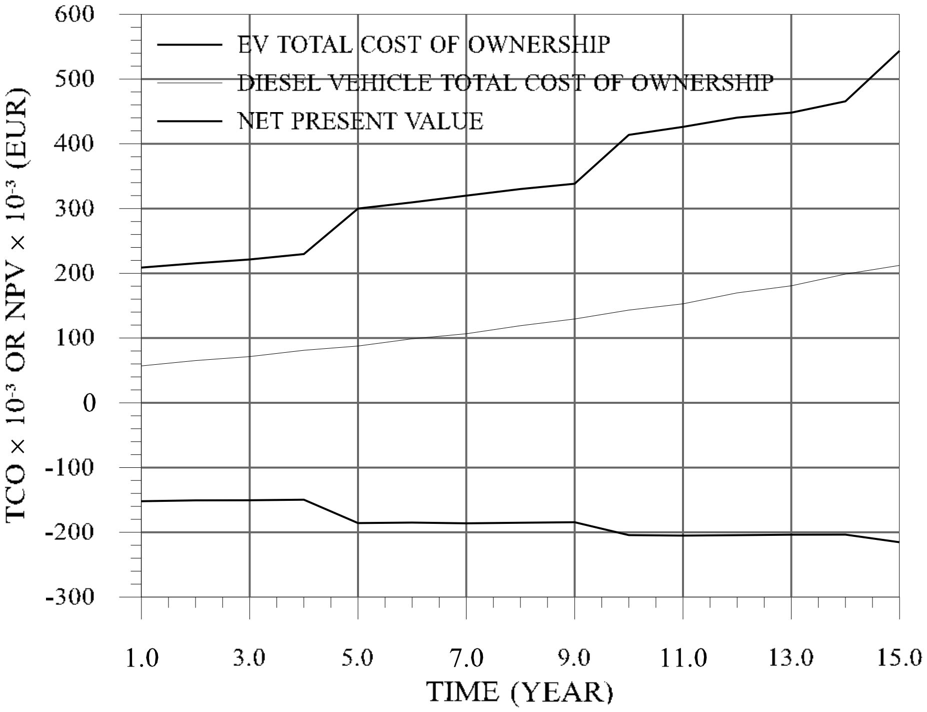


Figure 6 – Total cost of ownership (TCO) and net present value (NPV) of the electric and diesel vehicles along 15 years in the base case.

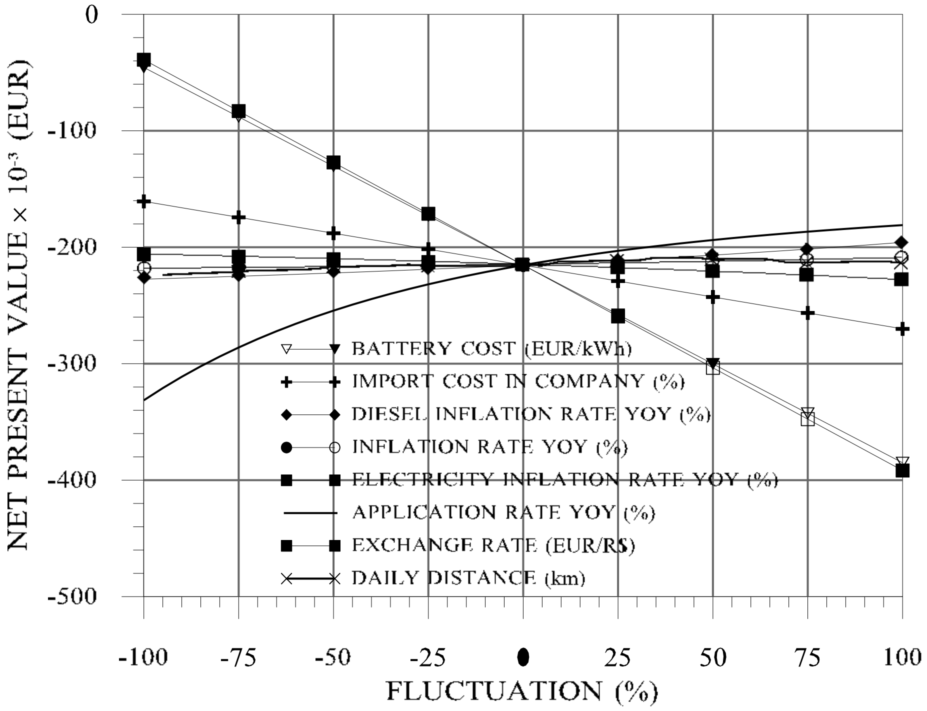


Figure 7 – Net present value (NPV) sensitive analysis in the base case (0). Inflation and application are expressed in year-over-year (YOY) change rates.

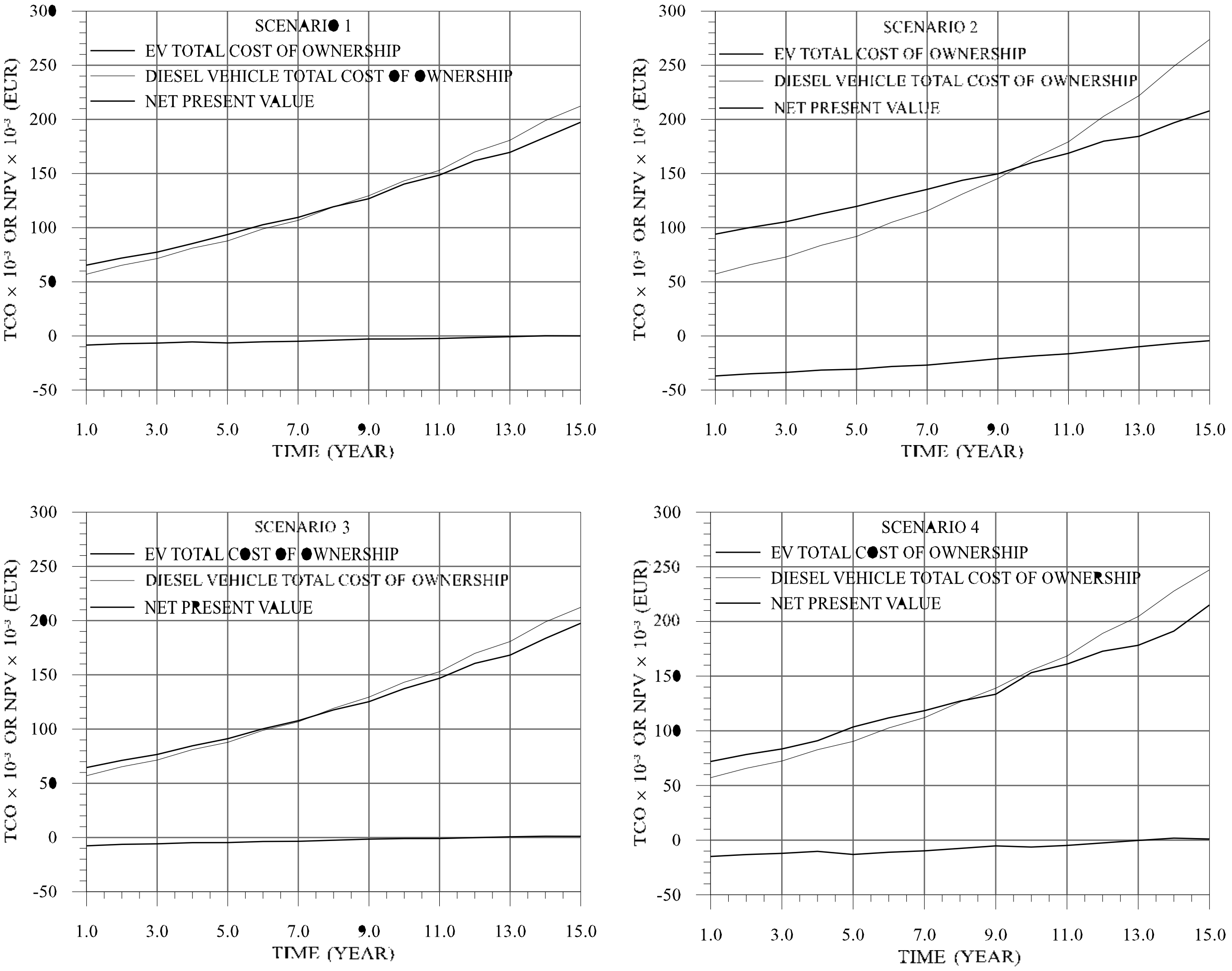


Figure 8 – Total cost of ownership (TCO) and net present value (NPV) of the electric and diesel vehicles for different scenarios (Tab. 5).

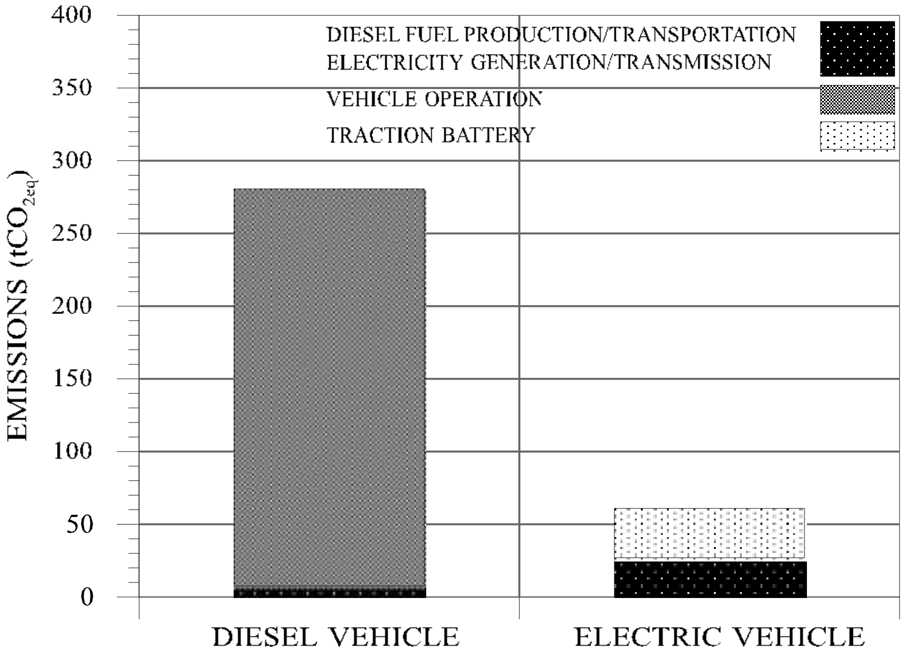


Figure 9 – Carbon dioxide (CO_2) emissions from the electric and diesel vehicles.

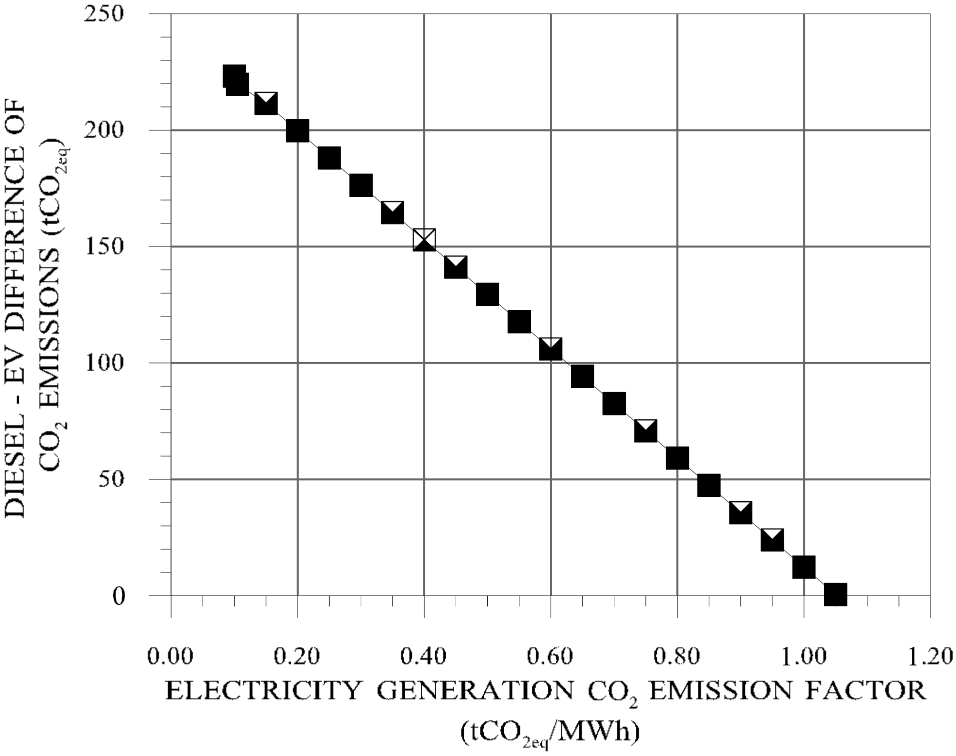


Figure 10 – Influence of the emission factor on the difference of CO_2 emissions from the diesel vehicle to the electric vehicle.

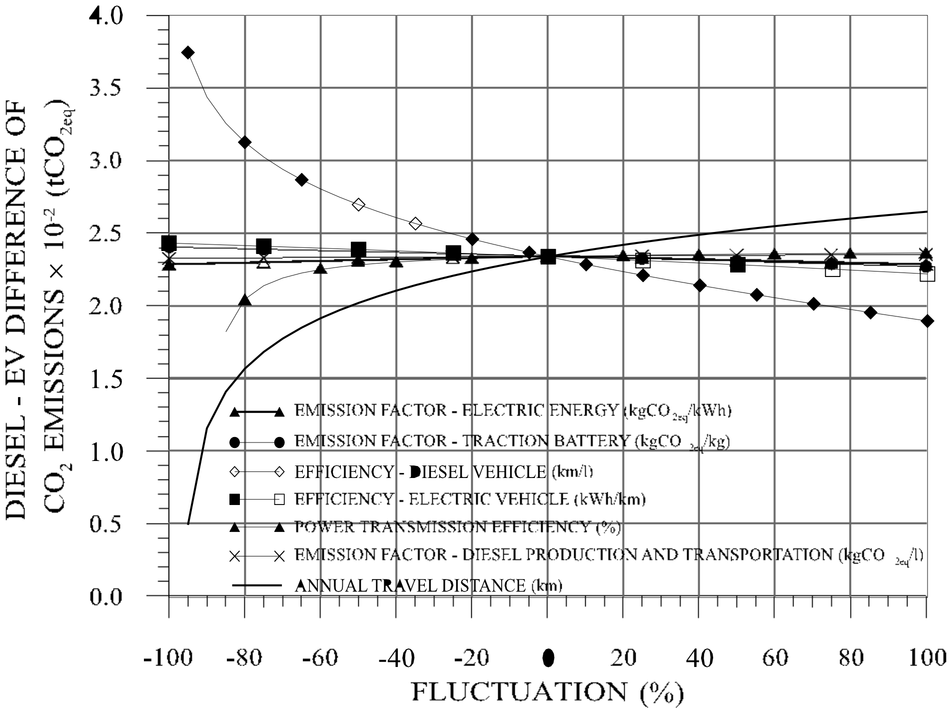


Figure 11 – Sensitivity analysis of the difference of CO$_2$ emissions from the diesel and electric vehicles.