MASTER

Modelling Long-haul electric truck adoption by comparing the total cost of ownership for fleet operators

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Award date:
2018

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Modelling Long-haul electric truck adoption by comparing the total cost of ownership for fleet operators

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ABSTRACT: The purpose of this study is to model realistic buying behavior and predict the profitability and feasibility of electric trucks for fleet owners. To accomplish this, bottom-up (agent-based) modeling was used. In order to predict the profitability of electric trucks, total cost of ownership (TCO) has been compared with that of diesel trucks by simulating realistic trips of an entire fleet on a GIS(Geographic information system) map of the Netherlands. Results suggests that the TCO is lowered if electric trucks replace part of the diesel trucks in the fleet. Within this study different charging types such as depot, fast and CAT-ERS charging have been considered to investigate their effect on the TCO per km. The model developed can be treated as an analyzing tool for understanding and predicting the profitability, and feasibility of electric trucks.

KEY WORDS: Total Cost of Ownership, Agent-based modeling, Electric truck

1. INTRODUCTION

Trucks account for nearly 39% of the life-cycle road vehicle greenhouse gas emissions, despite representing only 9% of the global vehicle stock as seen in the Figure1 [1]. Further, trucks are the primary means of road freight transport across all European countries [2]. They represent the Heavy-Duty Vehicle(HDV) segment with the largest share of energy consumption and CO2 emission [3]. In Europe, they account for approximately 40% of fuel use and greenhouse gas(GHG) emissions [4]. Moreover, nearly 99% of new and in use heavy-duty vehicles are powered by diesel engines [5]. It is evident that the reason for transport GHG emission is from

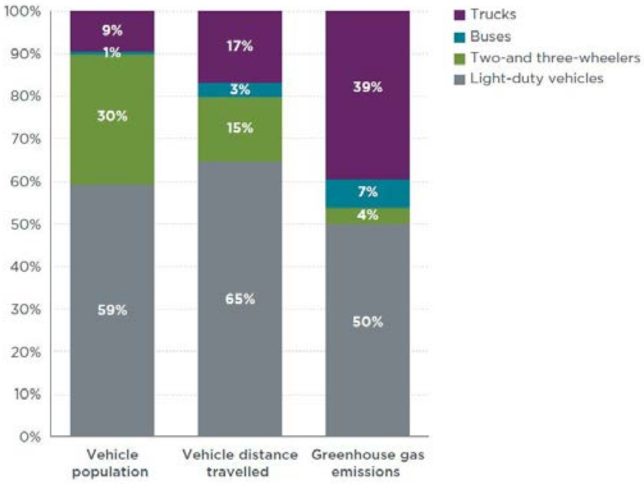

Figure 1: Percentage representation of the different vehicle population and their respective GHG emissions.

burning diesel fuel and it is one of the substantial operating costs for the trucking industry [5]. While pollution is majorly caused by moving trucks, idling the trucks overnight also cause significant pollution and increase fuel consumption[6]. European Union has set a target to reduce 40% of the GHG emissions by 2030 [3]. To achieve this climate change mitigation target, pollution from heavy-duty vehicles should be considerably reduced.

Port of Rotterdam in the Netherlands could be an interesting business case to analyze because enormous number of containers arrive and depart every year. For instance, in 2015 and 2016, nearly 7 million containers arrived in and out from the port of Rotterdam [7]. A large number of containers are then transported on the heavy-duty trucks to a logistic location before reaching their respective destination. So these trucks contribute significantly to GHG emission. Therefore, electrifying the corridor or route connecting the Venlo and port of Rotterdam can contribute significantly to reducing the GHG emissions. This would also showcase as an example for other important routes across Europe to be electrified, and result in overall reduction in GHG emissions. To achieve this goal in long-term, feasible and reliable alternate powertrain options must be found to replace diesel trucks. In Evas et al. [8] it is recommended that currently the only feasible and marketable zero emission vehicle alternative to ICE are the Battery electric vehicles (BEV) and the Fuel cell Vehicles (FCV). Moreover, the study also remarks that in terms of manufacturing, fueling and infrastructure investments the BEV's are immensely inexpensive and more efficient. Therefore, battery electric trucks could be considered as viable alternatives for diesel trucks. However, the existing fleet-owners could be hesitant towards adapting electric trucks. In other words, fleet-owners would not be completely convinced by the electric powertrain or influenced by the performance of the electric truck. This is because of the factors such as higher purchase price, range anxiety, payload carrying ability and charging time and infrastructure. All these factors are predominantly due to the present battery technology. In addition, the reliability of the long haul electric trucks cannot be assured as there are no sufficient real-world data to accurately predict the future for e-mobility [9]. On the contrary, many automotive Original Equipment Manufacturers (OEM) such as Tesla, Daimler, Renault, Nikola Motor Company and E force among few others are developing and few have already showcased the electric semi-truck concepts [10].

Wide options of these novel concepts are governed by factors such as battery technology, charging infrastructure, government actions and also most importantly early adopters. Moreover, when making a purchasing decision, the cost of buying and operating a vehicle plays an important role for any potential buyers [10]. But a majority of the buyers are unaware of the fact that the operating cost of an electric vehicle is significantly lower than ICE vehicles. This is because buyers perceive electric vehicles to be significantly expensive due to their higher purchase cost [11]. By providing buyers with the information on the TCO metric which includes vehicle associated costs over a period of ownership will address the misconception related to electric vehicles[12]. Therefore, by considering the total cost of ownership a clear and understandable cost comparison between diesel and electric trucks can be established. Thus, the research question for this study is formulated as:

How to model realistic buying behavior of electric trucks for fleet owners considering the Total Cost of Ownership?

Sub-question:
Can this model include charging behaviors?

There have been very few studies in the literature reporting on the adoption of heavy-duty electric trucks based on cost comparison. A cost model based on a transport application was developed with four steps which compared the future commercial vehicle powertrain technologies [13]. This study introduced a techno-economic approach for the assessment of the future technologies. Similarly, a study in [14] uses Matlab-Simulink model of a battery electric truck to analyze the battery size requirements, energy consumption and life cycle costs for a Gross Vehicle Weight (GVW) of 40T. This study also considers slow and fast charging methods to compare the life cycle costs with the diesel truck for a transportation scenario in Germany. Furthermore, the study in [15] uses parametrized vehicle dynamic model to investigate the trade-off between the initial investment and operating cost associated with both electric and diesel semi truck. These studies are based on a mathematical model which uses top-down approach and can be difficult to incorporate energy transitions, heterogeneous actors, interaction of multiple actors in space and time, and evolving technologies. These are necessary to comprehend the emerging electric truck market as it mainly deals with potential buyers and charging market investors apart from technical aspects. Therefore, incorporating the behavior of actors and analyzing the problem bottom up with a cost comparison between the diesel and electric truck would provide knowledgeable insights into this complex transport ecosystem. Furthermore, modeling a complex system with a bottom-up approach can produce better quality when compared to a top-down approach [16].

The complex system with energy transition, heterogeneous actors with complex behaviors can be relatively easily modeled using agent-based method. The research by Auke et al. shows how agent-based modeling can be applied to capture complex technical systems with bottom-up creation [17]. This modeling method enables us to define both qualitative and quantitative aspects of the modeled system. However, this modeling method can be considered as a useful addition and not a substitute for system dynamics or discrete event modeling [18]. Recently, researchers have shown interest in applying agent-based modeling method for understanding the adoption of electric vehicles. The study in [19] uses agent-based modeling to analyze the buying behavior of the electric cars by simulating real neighborhoods in the Netherlands. Similarly, this modeling method has also been applied to see the effect of battery parameters such as energy density and cost influencing the EV adoption [20]. In another study, this modeling method has also been used to model rollout policies for charging infrastructure to study the EV adoption [21]. However, to the best of authors knowledge, no study has been found so far using the agent-based model for heavy-duty electric truck adoption. This study demonstrates the agent-based methodology for modeling and analyzing the profitability and feasibility of electric truck based on the total cost of ownership.

2. MODEL DEVELOPMENT DESCRIPTION

Electrifying the corridor/route connecting the port of Rotterdam and Venlo has a very interesting business case for electric trucks because of the container transport operation. According to the report from the port of Rotterdam, about 19% of the containers from the port of Rotterdam are transported by trucks across the border through Venlo [22]. Moreover, Venlo is ranked number one for most desirable logistic location across Europe as it is close to major consumption centers and transportation infrastructures [23]. Analyzing whether electric trucks can operate between this route considering charging infrastructure, and to make comparisons with the diesel truck would educate the fleet-owners to consider alternate options. Further, this would help predict the profitability and feasibility of electric trucks. Moreover, a fleet-owner who can adapt electric technology if not completely would at least pave the path towards early adoption.

Finding a business case that best fits into alternate technology could be hard sometimes but even harder is understanding the complexities involved in it. For example, complexities such as variations in the number of trucks owned by fleet-owners, type of truck configuration, payload weight, location of the fleet-owner, charging types and associated costs are few of the factors. Therefore, to better understand and gain insights into the complex details involved in the system, modeling with the right level of detail can be very helpful. As can be seen, the Figure 2 illustrates how Agent-based modeling (ABM) can be used for modeling different details of abstractions right from low level to high level. With ABM, complex systems such as heavy-duty truck transport business which involves heterogenous demographics such as fleet-operators, stakeholders, economic aspects and most important developments in electric technology can be modeled easily without compromising on the details. Furthermore, system dynamics and discrete events can also be incorporated in this method to showcase details relative to ABM.

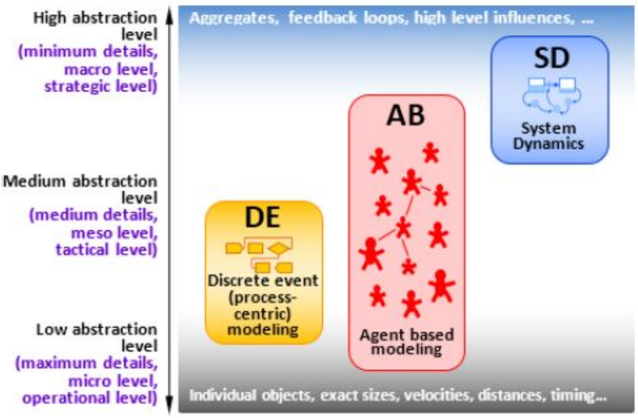

Figure 2 : Different abstraction levels which can be assumed in three methods of simulation modelling [24, p. 13]

2.1 Fleet owner buying behavior model framework

This model analyses the profitability and feasibility of electric trucks for fleet owners by comparing the total cost of ownership for the port of Rotterdam business case. This model has been developed on a modeling tool-Anylogic. This tool can be employed for multimethod simulations such as agent-based, discrete events and system dynamics [25]. Although this model stands on itself, it has been improved further by interactions with the charging model [26]. This model has been developed by following the steps provided in [27]. After defining and formulating the problem, the next step in model development is identifying important actors or objects involved in the system. The actors are considered as an agent if they perform independently and make their own decisions and they are recognized by their states, behavior, and the ability to interact with each other. Moreover, they are considered as a fundamental unit of the model [27, p. 79]. The agents considered in this model are:

- Fleet-owners
- Customer order
- Diesel truck
- Electric truck
- Start point
- End point
- Charge point.

Once the agents have been determined the next step is defining agents with specific properties or states that describe their function. The detailed explanation of the agent properties and behaviors are mentioned in the next section. In our model, for example, an electric truck interacts with charge point whenever it requires charging. Moreover, the agent interactions and movements are modeled and illustrated realistically on the GIS map of the Netherlands as shown in Figure 3. The GIS map is marked as an environment focusing on the route or corridor between the Port of Rotterdam and Venlo.

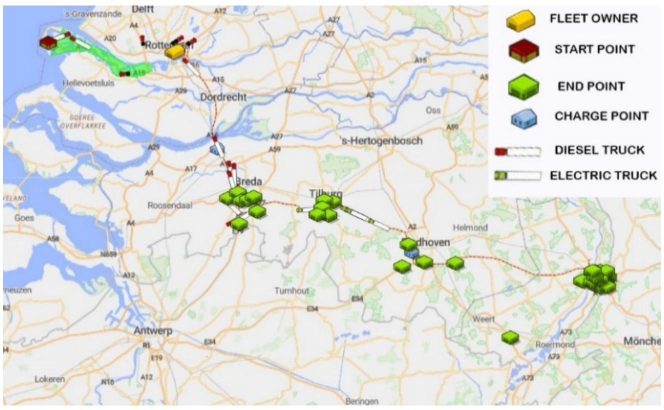

Figure 3: Overview of the GIS map of the Netherlands with different agents in the model

2.2 Agents in the model:

Fleet owner: They own a certain number of trucks and are located at the fleet owner location as shown in Figure 3. The most common type of tractor and trailer in EU is cab-over-engine with two axel configuration, and side curtain-type with three rear axles respectively [3]. Therefore, we assume that the trucks owned by the fleet owner are of this configuration and is shown in Figure 4. Fleet-owner accepts delivery orders from the customers located at the EndPoint. In the model, the customer order is directly received by the truck. The details involved in the order processing within the fleet owner organization is disregarded. This is because the details are unnecessary to solve the problem.

Figure 4: Representation of the typical Tractor-Trailer configuration seen in EU for long haul transport

EndPoint: This is the location agent as shown in Figure 3, and it is where the customer order is generated and sent to the fleet-owner. In this model, customer order is considered as an agent and not the customer because we only need the order information.

CustomerOrder: CustomerOrder is an agent which performs like a function within the agent EndPoint. This agent provides the payload data and the delivery location(EndPoint) to the fleet-owner for every single generated order. This is an agent type whose animation is not shown on the GIS map.

StartPoint: This is the location agent where the order is picked and then its delivered to the EndPoint. The location can be seen on the map as shown in Figure 3.

DTruck: This is a diesel truck agent as shown in Figrue 3, which can carry a maximum allowable payload. The dynamic behavior of the truck agent movement is modeled using state-charts and system dynamics libraries provided in Anylogic tool. Moreover, with the state-chart possible state of the agent movement across the GIS map along with the transition events are described. Further, energy consumption dynamics are modeled using a stock and flow diagram. As the truck mvoes on the GIS map energy consumed is calculated dynamically by the formula 1, and the cost incurred for the consumed energy is calculated by the formula 2.

$$Energy\ consumed \text{ per hour [liter]} = Speed\left[\frac{Km}{hr}\right] \times energy\ consumption\left[\frac{liter}{km}\right] \times Time\ [hr] \quad (1)$$

$$Cost\ for\ energy\ consumption\ [Euro] = \text{Energy consumed per hour [liter]} \times \text{Energy Cost}\left[\frac{Euro}{\text{liter}}\right] \quad (2)$$

Further, maintenance cost associated with a truck is also considered and is calculated per kilometer by the formula 3.

$$Maintenance\ Cost\ [Euro] = Total\ distance\ travelled\ [km] \times maintenance\ cost\ per\ km\left[\frac{Euro}{Km}\right] \quad (3)$$

In this model truck driver is not considered as an agent but the cost associated with the driver is calculated by the formula 4.

$$Driver\ Cost\ [Euro] = \frac{Total\ distance\ travelled[km]}{Speed\left[\frac{km}{hr}\right]} \times driver\ cost\ per\ hour\left[\frac{Euro}{hr}\right] \quad (4)$$

The energy consumption cost, maintenance cost, and the driver cost are considered as a varying operating cost. Additionally, tax and insurance are added as a fixed operating cost. The sum of the varying operating cost, fixed operating cost and purchase price of the truck is considered as the TCO. The CO2 emitted for the amount of fuel consumed is calculated as shown in the formula 5, by an energy-based approach provided by [28, p. 4].

$$CO_2\ emission\ [Kg.CO_2] = Fuel\ consumption\ [liter] \times fuel\ emission\ conversion\ factor\left[\frac{Kg.CO_2}{liter}\right] \quad (5)$$

Fuel emission conversion factor for the diesel fuel is considered as 2.9 [28, p. 5].

ETruck: This is an electric truck agent as shown in Figure 3, and it operates on a given payload and distance condition. These conditions are explained in detail in the next section. Similarly, state charts and system dynamics are employed to model the dynamic behavior of the truck. Further, the TCO for this truck is calculated similarly as shown for the DTruck agent except energy cost is calculated as shown in the formula 7, based on the charge request. However, the units for energy consumption and energy cost are replaced as [KWh/Km] and [Euro/KWh] respectively. Moreover, the energy cost for this agent varies dynamically based on the type of charging used.

$$Cost\ for\ energy\ consumption\ [Euro] = \text{Energy requested } [KWh] \times \text{Energy Cost}\left[\frac{Euro}{\text{KWh}}\right] \quad (7)$$

Charge point: This is a charge point agent located on the GIS map as shown in Figure 3. Whenever electric truck utilizes the charge point, the cost for requested KWh will be added to the TCO based on the type of charging such as fast charging or slow charging(depot charging). Moreover, the time required to charge a truck is determined based on the capacity of the charger installed and is calculated by the formula 8.

$$Charge\ time\ [hour] = \frac{Charge\ requested\ [KWh]}{Capacity\ of\ the\ charger[KW]} \quad (8)$$

Main: As the name suggests this is the agent where all the above-mentioned agents and their population are situated, and they interact both in time and space. This agent also contains global parameters, variables, and functions used in the model.

2.3 Simulation narrative of the model

At first the locations of the fleet-owner, customer, charge points and payload pick up point are loaded on to the GIS map. Secondly, the simulation is started after the initialization of the parameters. Further, assumptions on the parameter selection are explained in the next section. In the simulation, the diesel truck starts its operation once the customer sends the delivery order request. This order will have the payload weight which is randomly generated by a custom distribution function and is shown in the appendix A. However, for the electric truck to start its operation there is two conditions which has to be satisfied. The first condition is the payload condition and it checks whether the sum of the electric truck curb weight and payload weight is less than or equal to the GVW. This condition is necessary because heavier payload cannot be transported due to the weight of the battery affecting the GVW limit. If this condition is not satisfied, then the electric truck will not accept the order. If this is the case, then the order is transferred to the diesel truck if it is available. Secondly, a distance condition is specified to make sure that the electric trucks accept only those delivery orders that can make complete use of the assumed battery capacity. In addition, delivery orders which are closer and can accommodate two trips a day could also make complete use of the battery. But in our model, two trips a day is only considered for the diesel trucks and is disregarded for the electric trucks to make simple trip selection algorithm. Moreover, if the delivery order is not in the electric trucks range then it is transferred to the diesel trucks if they are available. Further with an advanced algorithm, dynamic trip selection based on distance could be achieved, however, this would add to computation burden and increase simulation time.

There is also condition on the number of trips that can be completed successfully by both the trucks in one day because the driver can drive only 9 hours per day [29]. Further, according to this reference driving time can be exceeded to 10 hours with an exemption of twice a week, but in our model, this exemption is not considered. As the truck starts moving the energy consumed and all associated costs such as energy cost, maintenance cost and driver cost are calculated dynamically and added to the TCO. Additionally, for the electric truck, an extra time-related cost or waiting cost is added whenever a truck driver must wait for charging. Electric truck is charged only up to a certain limit which is sufficient enough to reach the fleet owner location whenever the truck charges at the fast charging point. This is because the truck can be charged using a depot charger with less cost when compared to fast charging. Moreover, when the truck enter the CAT-ERS region, energy consumption from the battery is terminated and cost of energy consumption is determined from the KWh used from the CAT-ERS. Further, the TCO is determined once the truck completes the trip and returns to the fleet-owner location. This process is carried out dynamically for different trips made by various trucks over a period. Finally, the entire TCO of the fleet is determined once the simulation is completed.

3. SCENARIO ANALYSIS AND RESULTS

To answer the question of whether buying electric trucks would be profitable for fleet operators certain scenarios have been investigated in this study. The base scenario is that fleet owner is assumed to be located at Rotterdam and has only diesel trucks in his fleet. Further, the fleet-owner receives delivery orders from the customer located at various locations as shown in the appendix C. The order (container) must be picked up from a container terminal located at Maasvlakte in Port of Rotterdam and delivered to the respective customer location. After the delivery, we assume that the empty container is transported back to the terminal and then the truck returns to the fleet owner location. From the expert opinion loading and unloading time is assumed to be 1 hour. For this scenario parameters initialized are shown in the Table 1.

Parameter	Value
Number of diesel trucks	40
Energy consumption [Liter/km]	0.326[1)]
Fuel capacity [Liter]	500[1)]
Fuel cost [Euro/liter]	1.2
Maintenance cost [Euro/Km]	0.064[2)]
Driver cost [Euro/hr]	26[3)]
Purchase cost of the tractor-trailer [Euro]	150000[3)]
Insurance [Euro/year]	5000
Tax [Euro/year]	856
Curb weight of the tractor-trailer	15T[1)]

Table 1: Parameters initialized for the base scenario. 1)The values for curb weight of tactor-trailer with 500 liter capacity and fuel consumption has been adopted from the report [30]. *2)Maintenance cost value has been adopted from the report* [31]. *3) Driver cost and purchase cost has been adopted from speaking to fleet operator.*

The first step is to determine the optimal ownership period for the diesel trucks to be in operation. From expert (ASDA and Ashok Leyland) recommendation the period of ownership for the trucks was found to be 5 years because after this period TCO per km would increase due to the higher maintenance cost. Therefore, to find out this maintenance cost a trial simulation with different maintenance cost increment was carried out with the initialized maintenance cost parameter. After certain simulations, a maintenance cost that would affect the TCO per km after 5 years was determined and is as shown in Figure 5 . Following this, depreciation of the truck is calculated for 5 years as shown in Appendix B by taking distance traveled by the truck from the simulation. Further, the calculated values for the depreciation and maintenance cost are used for the scenario. Now with this initialized parameters, TCO per km for this scenario has been determined as shown in Figure 6.

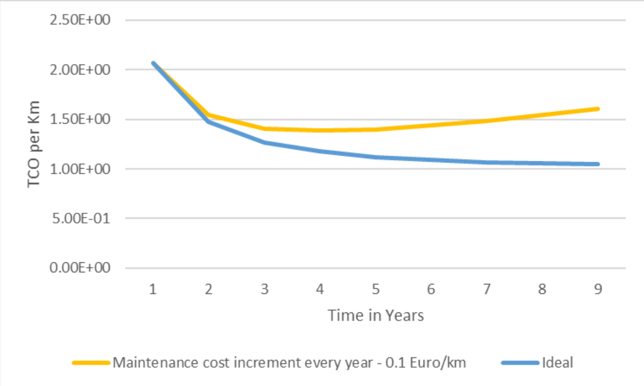

Figure 5: TCO per km for 40 trucks with maintenance cost increment.

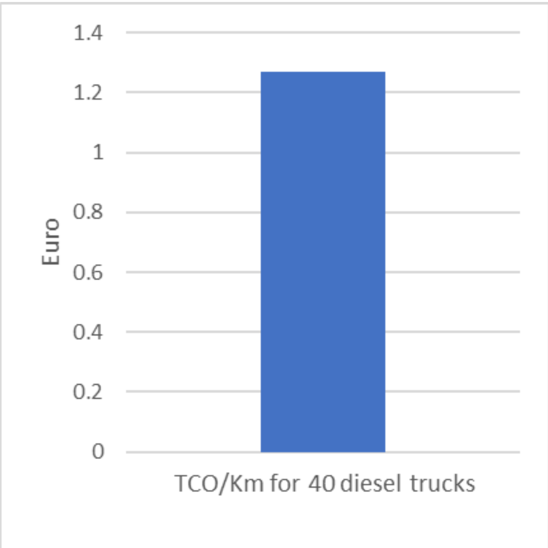

Figure 6: TCO per Km for the entire fleet of 40 diesel trucks

Scenario 1: Adding electric trucks to the fleet, and with only the depot charging facility

Electric trucks are added to the base scenario for analyzing the profitability and feasibility. In addition, to simulate the situation of unavailability of fast charging infrastructure only depot or overnight charging has been assumed for this scenario. At first, by looking at the customer locations from the GIS map battery size has been assumed to be 790KWh to facilitate the two way trip of Rotterdam-Maasvalkte-Venlo region which is about 520 km. This range would be ideal to test as Tesla claims a range of around 500 Km for one of their base semi model [32]. However, certain delivery locations in our model are not in the range of the electric trucks and those are left for the diesel truck. Further, for this scenario distance condition for the electric truck is specified as explained in the previous section-simulation narrative and the following parameters for the electric truck are initialized as shown in Table 2. Since no data is available on electric heavy-duty trucks this study assumes the period of ownership to be 8 years considering the distance traveled from the simulation and limitation from the battery life. Further, with this assumed period of ownership depreciation for the electric truck is calculated as shown in Appendix B. For this scenario parameters initialized are shown in Table 2. The calculated values for the depreciation and initialized parameters are used for this scenario. After the simulation TCO per km has been determined for the entire fleet as shown in Figure 7. From this figure

Parameter	Value
Number of diesel trucks	39
Number of electric trucks	1
Energy consumption [KWh/km]	1.5[1)]
Battery cost [Euro/KWh]	100
Deopt charging cost [Euro/KWh]	0.18
Maintenance cost [Euro/Km]	0.044[2)]
Driver cost [Euro/hr]	26
Specific energy of the battery [kg/KWh]	5
Purchase cost of the electric truck including trailer but without the battery [Euro]	140000
Battery Capacity [KWh]	790
Purchase cost of the electric truck including trailer with the battery [Euro]	219000
Insurance [Euro/year]	5000
Curb weight of the truck without the battery	13T[(1)]
Curb weight of the truck with the battery pack (790 KWh)	16.95T
Charger capacity [KW]	150

Table 2. Parameters initialized for Scenario 1.

1) The value of energy consumption is considered by the manufacturers claim as explained in the study [33] *and also powertrain weight difference between diesel and electric is stated as 2.7T in the same study. So considering this, curb weight of the electric truck is assumed to be 13T.*

2) By excluding engine repair, lubricant, oil and Adblue cost and considering only the tyre cost given in the report [31], *the value of maintenance cost for the electric is determined.*

it is clear that TCO per km for the entire fleet with 1 diesel truck replaced with the electric truck is cheaper. Subsequently, number of electric trucks have been added to see their effect on the TCO per km as shown in the Figure 8. Therefore from the Figure 8, it can be seen that adding a sufficient number of electric trucks to the fleet will reduce the TCO per km for the entire fleet. According to this scenario, only 24 electric trucks could be added as there are 24 customer locations at Venlo region which can be operated by electric trucks with the assumed battery capacity. Rest of the locations are operated by the diesel trucks. Therefore, utilizing electric

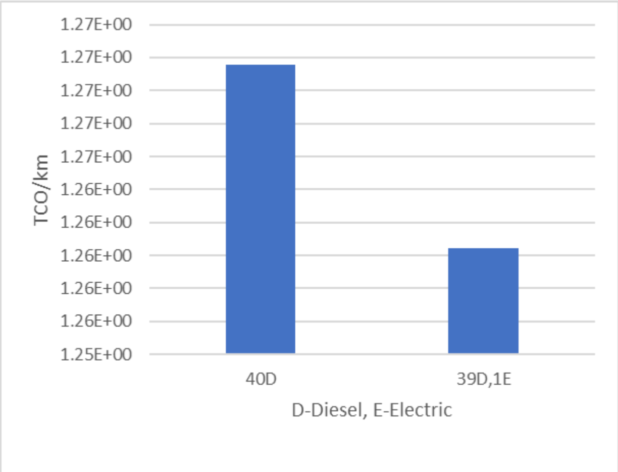

Figure 7: TCO per km comparision for the fleet of only diesel trucks and a fleet of combined diesel and electric truck

trucks only for operating certain long distance feasible trips and operating rest of the trips by diesel will significantly reduce the TCO per km for the entire fleet despite the higher investment cost on the electric trucks. The advantage of replacing diesel trucks with the electric truck is that overall fleet efficiency is improved and CO2 emission of the entire fleet is significantly reduced as shown in Figure 9.

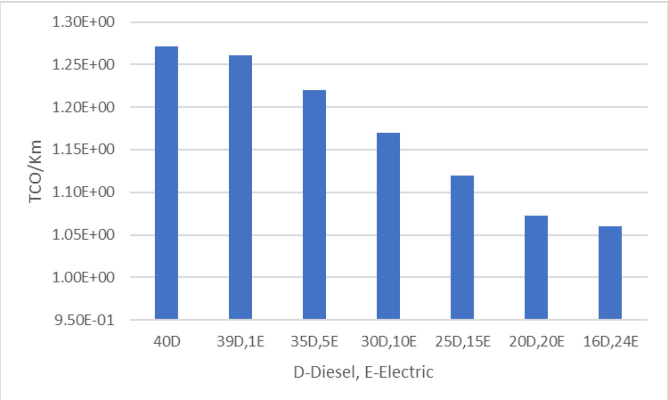

Figure 8: TCO per km for the fleet of combined diesel and electric truck with only depot charging

Scenario 2: Adding electric trucks to the fleet, and with both depot and fast charging facility

This scenario is similar to the previous scenario but only with the addition of highway fast charging points. So for this scenario, electric trucks can be charged both by depot and highway fast chargers. The fast charging points which are located near Rotterdam-Venlo highway

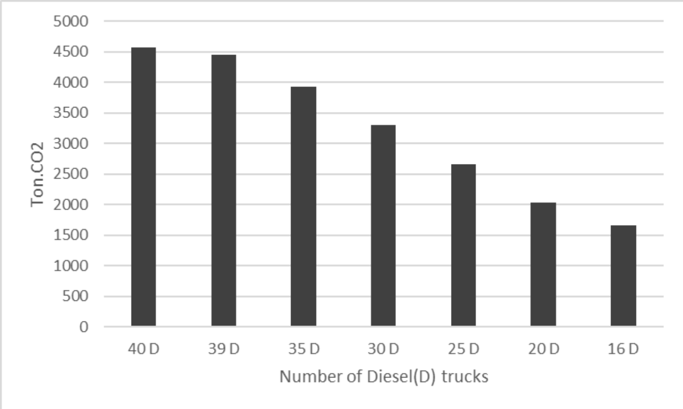

Figure 9: Reduction in CO2 emissions in Ton for one year with reducing number of diesel trucks in the fleet

are loaded from the google map on to the GIS map of the model. Further, battery capacity for this scenario was assumed to be 500 KWh as the range from this battery capacity was sufficient for the trucks to reach the destination due to having an option of charging from highway fast chargers, unlike only depot chargers as for the previous scenario. Due to the reduced battery size purchase price for the truck is also reduced to 190000 euros, curb weight of the truck is reduced to 15.5T and fast charging cost is assumed at 0.25 Euro/KWh. Further, fast charger capacity is assumed to be 650 KW. Rest of the parameters are same as considered for the previous scenario. Similarly, simulation has been carried out and TCO per km is determined as shown in Figure 10 for increasing number of electric trucks in the fleet.

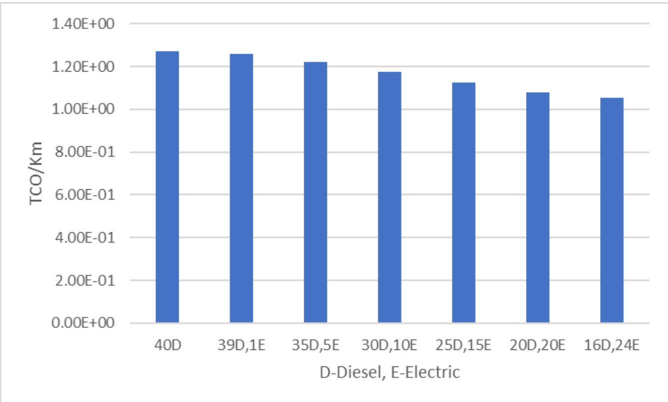

Figure 10: TCO per km for the fleet of combined diesel and electric truck with only fast charging.

From the Figure 10, it can be seen that TCO per km is reduced as the number of electric truck in the fleet is increased. However, comparing the two scenarios as shown in Figure 11, it can be seen that TCO per km for the scenario 2 is slightly higher for 5,10,15 and 24 Electric trucks despite the lower investment cost for the truck. This is due to the fact that cost for fast charging is higher when compared to the depot charging. Firstly, if the cost for the fast charging reduces then TCO per km for the scenario 2 will be lower. Secondly, using even smaller capacity battery would lead to lower TCO per km but will significantly affect the range of the truck and might not be feasible for long distance trips. But the only advantage with the scenario 2 is electric truck could carry a slightly heavier payload as battery size was smaller when compared to scenario 1. However, the time required to complete the trip by electric truck was higher

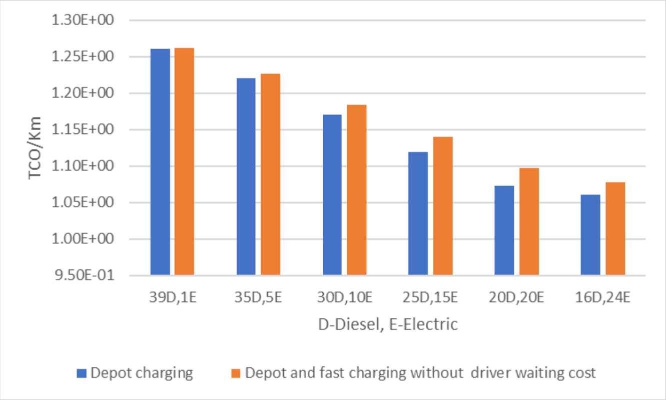

Figure 11: TCO per km for the fleet of combined diesel and electric trucks compared with only depot, and depot and fast charging.

than compared to scenario 1 as extra time was spent by the driver on charging the truck at fast charging points. So to compensate for this extra time a driver waiting cost of 35 Euro/hr has been assumed from expert opinion and the simulation has been carried out again with the same parameters as earlier. The results for this case is shown in Figure 12.

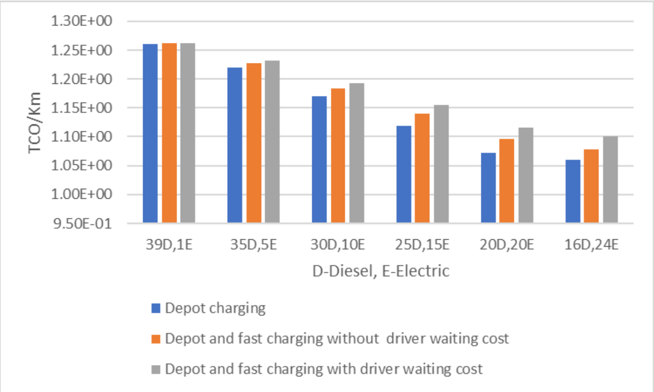

Figure 12: *TCO per km for the fleet of combined diesel and electric trucks compared with driver and without driver extra cost for depot and fast charging*

It can be seen that the driver waiting cost has a significant effect on TCO per km and will become expensive than the scenario 1 for fleet-owners. Therefore for fleet-owners, it depends on the flexibility of the customer to accept the late delivery and also pay for the driver extra waiting cost. One of the ways to reduce the waiting charge is to increase the capacity of the fast chargers. But in future with the introduction of the autonomous driving effect of driver cost on the TCO can be completely expunged.

Scenario 3: Adding electric trucks to the fleet, and with the depot, fast charging and CAT-ERS facility

In this scenario CAT-ERS charging is assumed to be in the region of Port of Rotterdam for a distance of 32km. CAT-ERS charging is a way of charging the trucks by the overhead electric lines. The electric Trucks will have a pantograph to connect to the overhead lines just like electric trains. Further, in this model, we assumed that energy provided from the electric lines is sufficient only to power the electric truck and will not be able to charge the battery. This scenario is to investigate whether introducing CAT-ERS charging facility would provide any advantage for the electric trucks and in turn benefit the fleet-owners. So for this scenario, electric trucks can be charged by the depot, fast chargers and CAT-ERS charging. Parameters for this scenario are same as considered for the previous scenario and cost for CAT-ERS charging is assumed to be 0.25 Euro/KWh. However, the weight and cost of the pantograph have been neglected for this study. With the initialized parameters, simulation has been carried out and the TCO per km is determined. The obtained result is compared with the previous scenarios as shown in Figure 13.

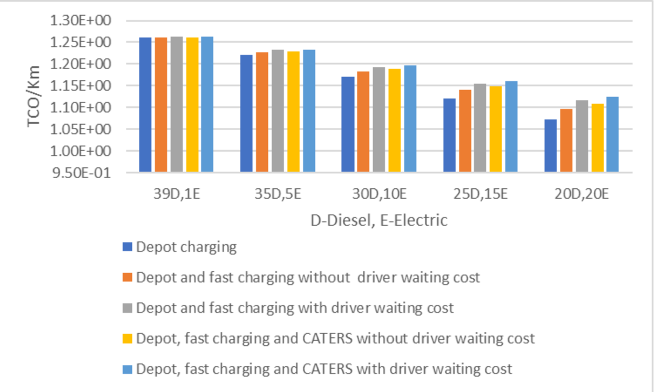

Figure 13: TCO per km for the fleet of combined diesel and electric trucks compared with driver and without driver extra cost for three types of charging

From the figure 13, it can be seen that with the addition of CAT-ERS charging the TCO per km for the entire fleet is significantly higher for all different number of diesel and electric truck fleet when compared to both depot, and depot and fast chagrining case. This is due to the higher cost of charging using CAT-ERS. But an advantage of using CAT-ERS for charging the truck is that energy is not consumed from the battery to power the truck for a distance of 32 Km at Port of Rotterdam. This translates to an extra range for the electric trucks. Therefore for this scenario, electric truck could operate for longer two way trip of around 584 Km (Rotterdam-Maasvalkte-Duisburg) as opposed to 520Km (Rotterdam

-Maasvalkte-Venlo region) with the same battery capacity as assumed for the scenario 1 and 2.

Scenario 4: Reducing the cost of fast and CAT-ERS charging to 0.15 Euro/KWh

In this scenario cost for the fast and CAT-ERS charging is assumed to be 0.15 Euro/KWh, which is 0.03 Euro/KWh lower than the depot charging cost. This is to check the effect of reduction in fast and CAT-ERS charging cost on the TCO per Km for an entire fleet of combined electric and diesel. Rest of the parameters are the same as initialized for the previous scenario. With the initialized parameters, simulation has been carried out and TCO per Km is determined as shown in Figure 14.

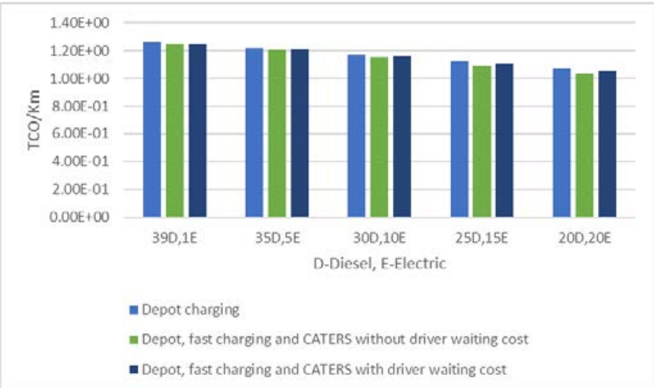

Figure 14: TCO per km for the fleet of combined diesel and electric trucks compared with only depot charging and depot, fast and CAT-ERS charging with reduced cost for fast and CATers charging.

As can be seen from the Figure 14, with the reduction in cost for fast and CAT-ERS charging the TCO per Km for the fleet is noticeably lower when compared to scenario 1. Therefore, this scenario suggests that the electricity cost has a significant effect on the TCO per Km.

4. CONCLUSION

In this research, an agent-based approach for modeling and analyzing the profitability and feasibility of electric truck based on TCO is demonstrated. This study shows that operating electric truck is profitable if the application is tailored to trips that maximize battery range without exceeding it. As battery technology progresses, more and more electric trucks become profitable. Further, the effect of different charging behaviors such as depot charging, fast charging, and CAT-ERS charging on the TCO per km have been analyzed. From the scenario analysis, it is determined that operating trucks with a larger battery(790KWh) for feasible long distance trips with just depot charging is cheaper than operating trucks with a smaller battery (500KWh) that is charged during the day using fast-charging and CAT-ERS, and with depot charging. But if the cost per KWh of fast charging and CAT-ERS would become lower than that of depot charging using a smaller capacity battery with the depot, fast, and CAT-ERS charging would result in a lower TCO. Furthermore, if higher capacity fast chargers are adopted, then driver waiting cost would be reduced significantly. However, adding electric trucks always lowers the fleet TCO irrespective of the type of charging. As our study shows, this model can be used to understand the complexities involved in predicting the profitability and feasibility of electric trucks for many kinds of business case and scenarios. Moreover, this model can be a tool in helping fleet-owners to make the right buying decision and understanding whether electric trucks will be profitable for their business.

5. FUTURE WORK

In the current model certain customer locations, fleet-owner location and trip pattern are assumed due to the unavailability of timely data. With actual data on trip patterns and locations, a more accurate TCO can be determined. A project to do exactly this(using data of the Port of Rotterdam) is currently underway. Moreover, in this model different truck brands and their specifications can easily be compared by considering each truck as a different agent type. In this way, the effect on the TCO of different truck types can be simulated.
This model does not take into account the battery replacement cost and degradation factors. Adding these factors would yield a more accurate TCO but currently, reliable data is not available in the public domain. Finally, this model can be extended to analyze the feasibility of vehicle to grid (V2G) behavior for heavy-duty truck fleet operation.

ACKNOWLEDGEMENT

I would like to express my gratitude to supervisors drs. Auke Hoekstra and prof.dr.ir. Maarten Steinbuch for providing me with an opportunity to work on this project and offered invaluable support and guidance throughout this journey. Special thanks to Port of Rotterdam for providing us with Bluetooth and WIM data. I would also like to thank Nazir Refa and Eric Beers for helping us with analyzing excel data and providing useful insights on the trucking industry respectively. Lastly, I would like to thank my colleague Norman who has been a part of this project.

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APPENDIX

A. Distribution for the payload

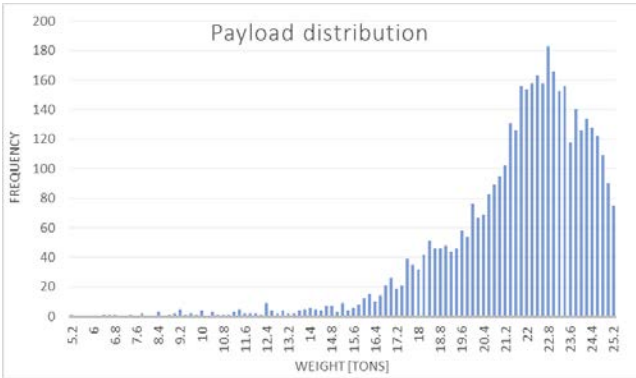

Figure 1: Frequency of payload weight carried by the 40T truck

This payload distribution histogram as shown in the Figure 1, has been created by considering the weight in motion(WIM)data provided from the Port of Rotterdam. The WIM data offers the total weight of the truck (GVW) for the class 40T and by this, the payload weight is determined by subtracting the total weight of the truck with the curb weight of the tractor.

B. Depreciation per km calculation

Depreciation for the diesel truck after 5 years is adapted to be 50% after talking to experts and distance traveled by truck for 5 years is found to be 609750 km from the simulation. Therefore, depreciation per km is calculated as shown below

$$\frac{Depreciation}{km} = \frac{Purchase\ cost \times 0.5}{distance\ travelled}$$

$$= \frac{150000 \times 0.5}{609750} = 0.123[Euro/km]$$

Distance traveled by the electric truck from trial simulation was found to be 140000 km every year. From this, we assume 8 years as the period of ownership because of the battery life limitation. Depreciation for the electric truck after 8 years is assumed to be 70% by learning from the diesel truck depreciation.

$$\frac{Depreciation}{km} = \frac{Purchase\ cost \times 0.7}{distance\ travelled}$$

$$= \frac{219000 \times 0.7}{1120000} = 0.137[Euro/km]$$

C. Customer Locations

In this model location of the customer are assumed to be in the highlighted area as shown in Figure 2. This data has been provided by the Port of Rotterdam. Furthermore, Duisberg in Germany is also considered as a customer location.

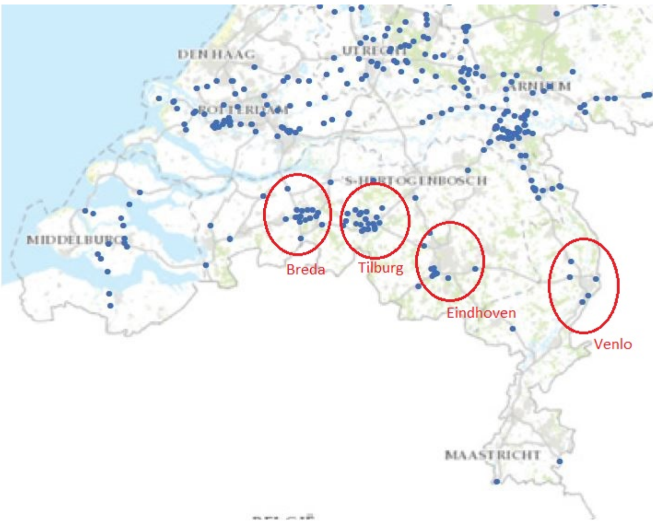

Figure 2: Location of the Bluetooth data points in the Netherlands.

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