

Impacts of Economic, Technological and Operational Factors on the Economic Competitiveness of Electric Commercial Vehicles in Fleet Replacement Decisions

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ABSTRACT

Electric commercial vehicles (ECV) have the potential to substantially reduce greenhouse gas emissions, noise, and pollution in urban areas. In addition, ECVs have lower per-mile operating costs and potentially lower maintenance costs. However, the initial purchase cost of ECVs is significantly higher than the purchase cost of a conventional diesel vehicle. From a purely economic perspective, there is a cost tradeoff between the low operating and maintenance costs of ECVs and their high initial capital costs. In this paper, a fleet replacement optimization framework is employed to analyze the competitiveness of ECVs. Scenarios with different fleet utilization, fuel efficiency and sensitivity analysis of ten additional factors indicate that ECVs are more cost effective when conventional diesel vehicles' fuel efficiency is low (8.2 miles/gallon) and daily utilization is more than 54 miles. Breakeven values of some key economic and technological factors that separate the competitiveness between ECVs and conventional diesel vehicles are calculated in all scenarios. For example, in low conventional diesel vehicle fuel efficiency and low daily utilization scenario, ECVs are more competitive when their purchase prices are less than \$135,586.

1. INTRODUCTION

The fast rate of commercial vehicle activity growth over the last decades and the higher impact of commercial vehicles externalities (e.g. congestion, noise, and pollution) are resulting in stricter government regulation in dense urban areas. Additionally, social and political pressures to limit the impacts associated with CO₂ emissions and fossil fuels dependence are mounting rapidly. Urban freight and commercial vehicles are responsible for a large share of unhealthy air pollutants such as sulphur oxide, particulate matter, and nitrogen oxides in urban areas [1]. Even if commercial diesel vehicles have a 10% share of total urban vehicle-miles traveled, commercial diesel powered vehicles can account for up to 90% of NO_x and particulate matter (PM) emissions [2].

Electric commercial vehicles (ECVs) are seen by many governments and environmentally friendly groups and organizations as a potential solution to address the impact of commercial vehicles noise, pollution, and GHG emissions in urban areas. However, it is not clear if ECVs are a viable solution given the large operational, logistics, and economic differences between ECVs and conventional internal diesel engines. In addition, the ECVs technology and economic characteristics are evolving more rapidly than the well-known and proven diesel technology.

Given the high capital costs associated with vehicle fleets, if fleet owners were to replace conventional diesel vehicles with ECVs, the replacement decision would be contingent on the result of a complete economic and logistics evaluation of the competitiveness of the new vehicle type. In addition, as vehicles age, their per-mile operating and maintenance (O&M) costs increase and their salvage values decrease. When the O&M costs reach a relatively high level, it may become cost effective to replace old vehicles since the savings from O&M costs may outweigh the high capital cost of purchasing new vehicles. Similarly, if fleet owners are interested in replacing conventional vehicles with new electric vehicles, it is important to understand how the O&M costs and salvage values change over time. Conventional diesel and electric commercial vehicles have significantly different capital and O&M costs.

To the best of the authors' knowledge this is the first research work that examines the competitiveness of diesel and electric commercial vehicles utilizing a fleet replacement optimization framework. In addition, a novel contribution of this work is to analyze the sensitivity and elasticity of the key economic and technological characteristics of ECVs.

The remainder of this paper is organized into five additional sections. Section two presents a literature review. Section three introduces the notation and formulation of the fleet replacement model that is utilized to optimize fleet management decisions. Section four describes data sources, assumptions, and evaluation scenarios. Section five presents and analyses the results of the optimization model as well as the elasticity and sensitivity analysis. Section six ends with conclusions.

2. LITERATURE REVIEW

Initiatives to encourage the adoption of ECVs are older and more popular in Europe than in the USA [3]. For example, an European project to foster the deployment of ECVs in urban less-than-truckload (LTL) deliveries took place between 1998 and 2002; this project named Electric Vehicle City Distribution (ECLIDIS) involved the establishment of urban distribution centers in six European cities [3]. A report commissioned by the European Union [3] concluded that the ECLIDIS program was a success but the report also admitted that both the cost of purchasing electric vehicles and their limited range were major barriers to their widespread implementation. Commercial electric vehicles are promoted in cities and countries that want to introduce more sustainable approaches to manage city logistics [4]; for example, in the Netherlands there are several cities and programs that encourage the adoption of ECVs [5].

There is a new generation of ECVs with better capabilities than the ones of the 1990's; still, purchase cost and range remain as two significant constraints [6]. Current commercial electric vehicles are characterized by a limited operational range; an optimistic assumption is a range of approximately 100 miles for a new vehicle. This range can be further restricted by the phenomenon known as "range anxiety," where drivers' anxiety regarding the limited range can lead to a reduction of the "practical" or real-world range by as much as 50% [7]. This limitation is more significant for commercial vehicles than passenger vehicles because the former tend to travel more miles and are used for more hours during a typical workday. For example, real-world LTL data from three different cities (Calgary, Denver and Amsterdam) indicates that, on average and each working day, 0.85 hours are spent driving from the depot to the customers and that an average of 3.95 hours are spent driving between customers; assuming average travel speeds between 10 and 30 miles per hour, commercial vehicles can easily travel between 39 and 118 miles per day [8]. These distances are considerably longer than the commute of typical American drivers [9].

Vehicle replacement models can be classified into two categories: research-oriented and practice-oriented. The latter are mostly simple heuristics. In practice-oriented models replacement decisions are usually made based on a set of criteria such as age, cumulative utilization, and maintenance cost thresholds. These are readily implemented heuristic models but suboptimal. A comprehensive review of practice-oriented models can be found in [10]. On the other hand, research-oriented models seek to economically optimize replacement decisions. The objective function is usually the minimization of total fleet costs over a given planning horizon. The research-oriented literature can be broken into two kinds of models: homogeneous and heterogeneous models. In the former, the objective is to find the best policy in terms of replacement timing for a set of homogenous assets [11], where optimal decisions for the same type of vehicles are the same; heterogeneous models are more appropriate when budget constraint is considered [12], for example, the same type and age of vehicles in a fleet may be replaced in different years due to restricted budget for purchasing new vehicles. There is no research work that addresses the competitiveness of commercial vehicles though the competitiveness of electric passenger vehicles has been studied [13-17].

3. MODEL FORMULATION

This is a deterministic model. Future costs such as purchase prices, fuel price, salvage values, maintenance costs, fuel and electricity consumption rate and many other economic and technical factors are assumed to be known functions of time (age) and vehicle type. Given the uncertainty associated to some parameters a sensitivity analysis is performed in Section 5.

Indexes:

Type of truck/engine: $k \in \mathbf{K} = \{1, 2, \dots, K\}$,

Maximal age of a type k truck in years: $i \in \mathbf{A}_k = \{0, 1, 2, \dots, A_k\}$,

Time periods, decisions are taken in each year: $j \in \mathbf{T} = \{0, 1, 2, \dots, T\}$.

Decision variables:

X_{ijk} = the number of age- i , type- k trucks used in year j ,

Y_{ijk} = the number of age- i , type- k trucks salvaged in the end of year j ,

P_{jk} = the number of type- k trucks purchased in the beginning of year j .

Parameters:

u_{ik} = utilization (miles traveled per year) of an age- i , type- k truck, (miles/year),

d_j = demand (miles need to be traveled by all vehicles) in year j , (miles),

b_j = budget (money available for purchasing new vehicles) in the beginning of year j , (\$),

dr = discount rate, to account for the decreased value of money over time,

h_{ik} = initial number of age- i , type- k trucks at the beginning of the first year,

v_k = purchase cost of a type- k truck, (\$),

s_{ik} = salvage revenue of an age- i , type- k truck, (\$), where $s_{0k} = v_k$,

o_{ik} = per mile operating (i.e., diesel or electricity) cost of an age- i , type- k truck, (\$/mile),

m_{ik} = per mile maintenance cost of an age- i , type- k truck, (\$/mile),

e_{ik} = per mile emissions cost of an age- i , type- k truck, (\$/mile),

fr_k = inflation rate for diesel prices over time.

$$\begin{aligned} & \sum_{j=0}^{T-1} \sum_{k=1}^K (v_k \cdot P_{jk}) \cdot (1 + dr)^{-j} - \sum_{i=1}^{A_k} \sum_{j=0}^T \sum_{k=1}^K s_{ik} \cdot Y_{ijk} \cdot (1 + dr)^{-j} \\ & + \sum_{i=0}^{A_k-1} \sum_{j=0}^{T-1} \sum_{k=1}^K [o_{ik} \cdot (1 + fr)^j + m_{ik} + e_{ik}] \cdot u_{ik} \cdot X_{ijk} \cdot (1 + dr)^{-j} \end{aligned} \quad (1)$$

Constraints:

$$\sum_{k=1}^K v_k \cdot P_{jk} \leq b_j \quad \forall j \in \{0, 1, 2, \dots, T - 1\} \quad (2)$$

$$\sum_{i=0}^{A_k-1} \sum_{k=1}^K X_{ijk} \cdot u_{ik} \geq d_j \quad \forall j \in \{0, 1, 2, \dots, T-1\} \quad (3)$$

$$P_{0k} + H_{0k} = X_{00k} \quad \forall k \in K \quad (4)$$

$$X_{i0k} + Y_{i0k} = H_{ik} \quad \forall i \in \{1, 2, \dots, A_k\} \quad \forall k \in K \quad (5)$$

$$P_{jk} = X_{0jk} \quad \forall j \in \{1, 2, \dots, T\} \quad \forall k \in K \quad (6)$$

$$X_{(i-1)(j-1)k} = X_{ijk} + Y_{ijk} \quad \forall i \in \{1, 2, \dots, A_k\} \quad \forall j \in \{1, 2, \dots, T\} \quad \forall k \in K \quad (7)$$

$$X_{iT k} = 0 \quad \forall i \in \{0, 1, 2, \dots, A_k - 1\} \quad \forall k \in K \quad (8)$$

$$X_{A_k j k} = 0 \quad \forall j \in \{0, 1, 2, \dots, T\} \quad \forall k \in K \quad (9)$$

$$Y_{0jk} = 0 \quad \forall j \in \{0, 1, 2, \dots, T\} \quad \forall k \in K \quad (10)$$

$$P_{jk}, X_{ijk}, Y_{ijk} \in I \in \{0, 1, 2, \dots\} \quad (11)$$

The objective function, equation (1), minimizes the sum of purchasing, operating, maintenance, and depreciation costs over the period of analysis, i.e. from year zero (present) to the end of year T . Purchase costs cannot exceed the yearly budget, equation (2). The total miles traveled by all used trucks should meet the yearly demand, equation (3). In the first year 0, the number of initial age-0 (new) trucks and the number of purchased age-0 trucks should be equal to the used age-0 trucks in year 0, equation (4). In the first year 0, the initial numbers of any types or any ages of trucks (other than age-0) should be either used or salvaged, equation (5). The purchased new trucks in all the other years should be equal to the number of used new trucks in each of those years, equation (6). The numbers of any used trucks in one year should be either used or salvaged in the next year, equation (7). It is assumed that all trucks will be sold in the last year of the planning horizon (T), equation (8). Any truck that reaches its maximal age will not be used anymore, equation (9). Any new purchased trucks cannot be sold immediately, equation (10). All decision variables must be non-negative integers, equation (11).

4. DATA SOURCES, INITIAL ASSUMPTIONS, AND SCENARIOS

This paper optimizes fleet replacement decisions in an environment where conventional diesel trucks (the incumbent) compete against electric vehicles (the challenger). For a fair comparison, only two trucks in a similar category (size) are compared. The conventional diesel truck is one of the popular Isuzu N-Series; the challenger the Navistar E-star is a new electric engine truck. The several significant truck characteristics and assumptions are summarized in Table 1.

Table 1 : A comparison of truck characteristics

Truck types	Isuzu	Navistar
Maximum age	$A_1 = 15$	$A_2 = 15$
Purchase price (\$)	\$50,000 ⁽¹⁾	\$150,000 ⁽²⁾
Energy consumption	13.46 ⁽³⁾ mile/gallon	0.8 ⁽⁴⁾ kwhr/mile (or 47.5mi/gal)
Energy price	\$4.06/gal ⁽⁵⁾	\$0.1068/kwhr ⁽⁶⁾

- (1) <http://www.isuzucv.com/>, an average price of all N-series trucks in 2010.
- (2) <http://www.automotiveworld.com/news/powertrain/82222-us-navistar-estar-truck-priced-at-us-149-900>, accessed May, 2010.
- (3) <http://www.isuzucv.com/news/fleetequipment09.html>
- (4) <http://www.estar-ev.com/specs>, 47.5mi/gal = \$4.06/gal / (\$0.1068/kwhr * 0.8kwhr/mile)
- (5) <http://www.eia.doe.gov/oog/info/gdu/gasdiesel.asp>, US Energy Information Administration, accessed June, 2011.
- (6) http://www.eia.gov/cneaf/electricity/epm/table5_3.html, electricity price for transportation, US Energy Information Administration, accessed February, 2011.

Henceforward we assume that $k=1$ for diesel trucks and $k=2$ for electric vehicles. Hence, according to Table 1, $v_1 = \$50,000$, $v_2 = \$150,000$. Ordering and delivery costs for purchasing new vehicles are not considered in this study. The salvage or resale value depreciates with age and cumulative vehicle mileage. Since the real-world resale values are driven by the market, there is no precise depreciation function for each vehicle type in the academic literature. A vehicle salvage value usually decreases concavely with age; a recent report [6] provides a series of concave curves for vehicle depreciation value as a function of age. The following recursive concave depreciation function is utilized in this research:

$$s_{ik} = (1 - \phi_k) s_{(i-1)k} = 0.85 \cdot s_{(i-1)k}, \quad \forall k \in K, \quad \forall i \in \{1, \dots, A_k - 1\} \quad (12)$$

The depreciation rate is denoted by ϕ . It is initially assumed that each year the vehicle loses 15% of the previous year value, i.e. $\phi_k = 15\%$ or 0.15.

In this study, the operating costs only include energy or fuel costs because it is assumed that the other major variable cost (driver salary) is not affected by the type of vehicle driven. Average vehicle energy consumption rates for the two trucks are shown in Table 1. Energy costs per mile for the Isuzu and Navistar vehicles are calculated using equations (13) and (14) respectively.

$$o_{i1} = \frac{\$4.06/gal}{13.46mi/gal} = \$0.302/mi, \quad \forall i \in \{0, 1, \dots, A_k - 1\} \quad (13)$$

$$o_{i2} = \frac{0.8kwhr}{mi} \times \frac{\$0.1068}{kwhr} = \$0.085/mi, \quad \forall i \in \{0,1, \dots, A_k - 1\} \tag{14}$$

The maintenance costs increase with vehicle age and utilization. We utilize per-mile maintenance cost for light-duty diesel trucks provided by [6]. For electric trucks, there are no long-term maintenance cost statistics. However, electric engine trucks are much simpler in design and thus likely to be cheaper in maintenance and repair costs. In addition, electric vehicles do not require oil changes and have less moving parts. Based on existing data and projections, we assume that electric trucks are 50% less expensive to maintain than conventional diesel trucks [6, 18].

$$m_{i1} = (0.2 + 0.04 \cdot i), \forall i \in \{0,1, \dots, A_k - 1\} \tag{15}$$

$$m_{i2} = (0.1 + 0.02 \cdot i), \forall i \in \{0,1, \dots, A_k - 1\} \tag{16}$$

As an initial condition, we assume that the carrier owns at the time of analysis (year 0) 30 Isuzus. The ages of the Isuzus are uniformly distributed with two vehicles per age from age 0 (two new vehicles) until age 14 (at least two vehicles must be retired at the end of year 0). The planning horizon is 30 years so all the initial vehicles must be replaced within year 0 and the end of year 14. Trucks are used between year 0 and year 29; all trucks are sold at market value at year 30. The discount rate is assumed to be 6.5% per year and the annual fuel/energy inflation rate is assumed to be 2.5%. The annual budget is assumed to be such that up to four electric trucks or twelve diesel trucks can be purchased each year.

Scenarios

Six scenarios are analyzed to study the impact of vehicle utilization and conventional diesel truck fuel efficiency on vehicle type purchases; fuel efficiencies and utilization levels are summarized in Table 2.

Table 2: Scenarios

Scenarios	Average annual utilization (mi/yr/truck)	Equivalent daily utilization (mi/weekday/truck)	MPG
S0	12,000 – AVG.	46	AVERAGE 13.46 mi/gal
S1	16,000 – GOOD	62	
S2	20,000 – HIGH	77	
S3	12,000 – AVG.	46	LOW 8.2 mi/gal
S4	16,000 – GOOD	62	
S5	20,000 – HIGH	77	

The total annual truck utilization is set at a level that requires that at least 30 trucks are required per year in each scenario. The high level of fuel efficiency (MPG or miles per gallon) is available at the official Isuzu website; the low fuel efficiency corresponds to the USA average of 8.2 mi/gal for urban delivery trucks [9].

Three annual utilization levels (12,000, 16,000 and 20,000 mi/yr/truck) are introduced to represent different levels of fleet utilization within the range of the electric truck, i.e. less than 100 miles without recharging. We denote these utilization levels Average, Good, and High respectively; according to USA statistics the average light-duty truck utilization in the USA is 12,000 miles per year [9]. Hence, we evaluate also scenarios with high utilization where the electric vehicle can be more attractive due to its lower operational and maintenance costs per mile driven. Although there is no utilization statistics for electric trucks, we assume electric trucks can be utilized as much as diesel trucks since the assumed annual mileage is lower than the electric truck potential mileage capacity of 26,000 miles per year; this is a practical optimistic upper bound (no range anxiety effects) for the electrical delivery truck assuming 52 weeks per year, five working days per week, and with the maximum range of 100 miles driven daily.

The baseline scenario (S0) is meant to represent “average” or existing market conditions assuming average utilization and the fuel economy of a new well maintained Isuzu truck. Given the uncertainty of some of the parameters, we also perform a sensitivity analysis and analyze breakeven points where the electric truck becomes competitive. Scenarios are denoted S0 to S5 as shown in Table 2.

5. RESULTS AND DISCUSSION

The optimal solution is determined by a combination of deterministic economic and vehicular characteristics. Results for each scenario are obtained utilizing a large scale mixed integer programming optimizer. This section is divided into three parts: (a) results regarding the impact of vehicle utilization and diesel fuel efficiency, (b) a breakeven analysis to understand when commercial electric vehicles become competitive, and (c) a study of the sensitivity of the results to changes in the values of base case scenario parameters.

(a) Scenarios

This subsection analyzes the impacts of vehicle utilization and diesel fuel efficiency on fleet management decisions. Table 3 summarizes the results of the six scenarios regarding vehicle purchases.

- In the baseline scenario, S0, ECVs are not purchased throughout the time horizon. The same takes place in scenario S1 despite the higher vehicle utilization.
- ECVs clearly become more competitive with a very high utilization (20,000 miles per year - S2) or good utilization level and low diesel truck fuel efficiency (S3). The lower fuel efficiency can be the result of driving conditions in congested areas with low speeds and stop and go traffic, excessive idling, or poor vehicle maintenance. Electric trucks are less affected by congestion since the batteries can recharge with the braking energy and the engine shuts down and does not idle when the vehicle is stationary. The main reason why ECVs become more competitive in S2 is that ECVs have less per-mile O&M cost and energy cost than diesel trucks, the more total miles traveled, the more cost savings from using ECVs compared to diesel trucks. Also, the key reason why ECVs are more economic competitive in S3 compared to S0 is because the diesel truck fuel efficiency is lower and therefore per-mile fuel cost is higher, and ECVs are more cost effective.

- Electric vehicles are clearly more competitive than conventional diesel trucks with good or higher utilization levels (20,000 miles per year) and low diesel engine fuel efficiency, scenarios S4 and S5. In these scenarios, already in the year zero the optimal decision is to buy ECVs to replace diesels trucks of age 13 and 14; this explains an initial market penetration of 13% for the electric trucks. This is true because ECVs have more advantage in high utilization and less diesel truck fuel efficiency scenarios.
- A good or high utilization is needed to overcome the high initial capital cost of electric vehicles. Electric vehicles will always be more appealing in routes or environments with low fuel efficiency for diesel engines.

Table 3: Scenario Results

		Diesel Fuel Efficiency					
		13.46 miles/gallon			8.2 miles/gallon		
Annual utilization (miles/year)		12,000	16,000	20,000	12,000	16,000	20,000
Equivalent daily (miles/day)		46	62	77	46	62	77
		S0	S1	S2	S3	S4	S5
Initial market penetration	Diesel	100%	100%	100%	100%	87%	87%
	Electric	-	-	0%	0%	13%	13%
Final market penetration	Diesel	100%	100%	67%	53%	0%	0%
	Electric	-	-	33%	47%	100%	100%
Average penetration	Diesel	100%	100%	51%	52%	11%	11%
	Electric	-	-	49%	48%	89%	89%

(b) Breakeven Analysis

Given the uncertainty associated to some economic or technological parameters, we perform a breakeven analysis to understand under what conditions ECVs become competitive. We define the breakeven point as the value of a parameter, *ceteris paribus*, that leads to the purchase of at least one any Navistar truck in year zero. For each scenario, breakeven points are found for 12 economic and technical factors as shown in Table 4.

The results of the breakeven analysis are intuitive. ECV price have to decrease between a 6% and 28% to allow electric vehicles to become competitive. For example, assuming scenario S0, the electric truck becomes competitive when the purchase price v_2 is less than \$107,870, i.e. the Navistar price should be reduced a 28% to become attractive enough to replace old Isuzu trucks (age 14 or older) with an electric truck instead of purchasing a new diesel vehicle. With higher utilization levels the price reduction needed is 16% and 6% for scenarios S1 and S2 respectively. As shown in Table 3, in scenarios S4 and S5 we do not perform the breakeven analysis because an electric vehicle is already purchased in year zero with utilization >16,000 miles per year and low diesel fuel efficiency.

Table 4: Breakeven analysis

Factors ↓	Scenarios →	S0	S1	S2	S3	S4 & S5	
General Factors							
Discount rate: dr	\leq	inf.*	2.3%	4.7%	4.2%	Already reached	
Annual utilization: u_{ik} (mi/yr)	\geq	22,272	22,272	22,272	14,138		
equivalent daily u_{ik} (mi/d)	\geq	86	86	86	54		
CO2 emissions cost: (\$/ton)	\geq	280	120.6	33.3	95		
Electric Vehicle Factors							
Electric truck price: v_2	\leq	\$107,870	\$125,852	\$141,691	\$135,586		
Depreciation rate	\geq	1.6%	4.5%	9.4%	7.3%		
Electricity price: (\$/kwhr)	\leq	inf.	inf.	0.062	inf.		
Electricity consumption: (kwhr/mi)	\leq	inf.	inf.	0.476	inf.		
Maintenance cost factor $x \cdot m_{i2}$	\leq	inf.	0.32	0.80	0.46		
Diesel Vehicle Factors							
Diesel price: (\$/gal)	\geq	8.1	5.8	4.6	5		
Energy Inflation rate: fr	\geq	25.6%	12.7%	4.9%	6.7%		
Diesel MPG (mi/gal)	\leq	6.7	9.5	12.0	6.7		

* inf. means infeasible, i.e. there is no realistic value of the parameter that make the electric truck competitive.

The parameters are broken into factors that apply to:

- Both types of vehicles, for example the discount rate (cost of capital) or utilization levels as well as an eventual carbon tax.
- Only electric vehicles, for example EV prices which are likely to go down when vehicles are mass produced or the EV depreciation rate that is an uncertain factor since we have not historical data for the new generation of electric trucks,
- Only diesel vehicles such as diesel prices, diesel inflation rate, or fuel efficiency.

We analyze the impact of a carbon tax assuming the electric vehicle not only has zero tail pipe emissions but also that it is charged with renewable carbon-neutral energy sources for simplicity.

The results indicate that:

- Very low (almost unrealistic) discount rate (2.3%) is needed to make the electric trucks competitive in S1 (median utilization and high diesel efficiency), and relative low (4.7% and 4.2%) discount rates are needed to make electric trucks more competitive in S2 (high utilization and high diesel efficiency) and S3 (low utilization and low diesel efficiency).
- The electric vehicle is competitive if its daily utilization is higher than 86 miles per day (over 22,000 miles per year) in high diesel efficiency scenarios (S0, S1, S2) and 54 miles per day (over 14,138 miles per year) in low diesel efficiency scenarios (S3, S4, S5). This assumes that batteries aging process does not reduce the practical age below 80 miles for 15 years. However, in practice these levels of utilization may not be achieved as the

vehicle/battery ages. It is uncertain the low term behavior and capacity of the current generation of batteries. The decline in range can be compensated by the increased availability of fast recharging stations in urban areas.

- If CO₂ emission cost is considered in fleet replacement decisions, electric trucks will have more advantage in cost savings. A penalty cost of \$33.3/ton for CO₂ emissions will make electric trucks more competitive in scenario S2 (or \$120.6/ton in scenario S1). Carbon taxes should be significantly higher than \$30/ton to have an impact on fleet management decisions. As a reference, current carbon taxes in the European cap and trade system are around \$18 per ton of CO₂ [19]. Emissions cost share only 5%-7% of total costs throughout the time horizon and therefore extreme high penalty cost of CO₂ are needed in S0 – S3 while no penalty cost of CO₂ are needed in S4 and S5.
- The electricity prices and energy efficiencies that are needed to make the electric truck competitive are clearly unattainable and unrealistic. Likewise, maintenance costs per mile must be very low to justify the purchase of ECVs in scenarios S1 and S3.
- Very low depreciation rates are needed in scenarios S0 and S1. Even if ECVs are highly reliable it is difficult to achieve depreciation rates of less than 5%.
- Current diesel fuel prices have to increase to the \$4.6/gallon- \$5.8/gallon range to ensure the competitiveness of electric trucks in scenarios S1 and S2. These numbers do not seem to unrealistic given the recent spike in oil prices. Alternatively, a high 4.9% or 12.7% diesel fuel price annual inflation rate is necessary in scenarios S1 and S2.
- Electric trucks are competitive in environments where diesel trucks achieve MPG lower than 6.7 miles/gallon in S0 and S3. This is unrealistic as diesel engines are progressively becoming more efficient and fuel saving devices can be added to reduce idling and limit vehicle accelerations.

Figure 1 illustrates the impacts of ECVs' depreciation rate on overall fleet cost per mile. We see that the results are not sensitive for depreciation rates that are more than 15%. However, there is a high impact on total fleet cost per mile when the depreciation is less than 10% and electric vehicles are purchased in large numbers.

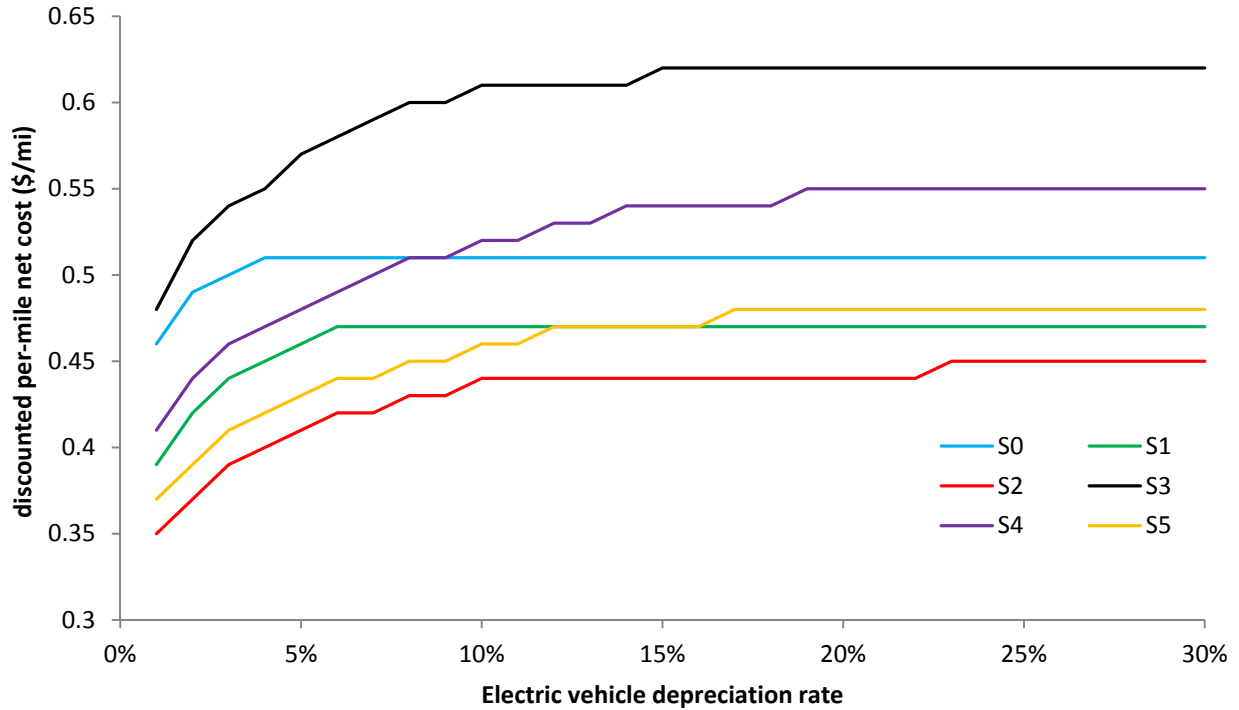


Figure 1 : Electric vehicle depreciation rate vs. total fleet per mile costs

(c) Elasticity Analysis

Finally we perform a sensitivity analysis to understand what factor has the highest impact on per-mile costs. We compute the elasticity of per-mile costs to each factor using the following an arc elasticity formula (18) where η_x^c is the elasticity of per mile cost c to parameter x :

$$\eta_x^c = \frac{(x_1+x_2)/2}{(c_1+c_2)/2} \cdot \frac{\Delta c}{\Delta x} = \frac{(x_1+x_2)}{(c_1+c_2)} \cdot \frac{(c_2-c_1)}{(x_2-x_1)} \tag{18}$$

We calculate the elasticity of total fleet per mile cost to each parameter assuming a range shown in Table 5. For example, for a discount rate, assuming that $x_1 = 4\%$ and $x_2 = 9\%$, the elasticity for scenario S0 is -0.64.; i.e. when the discount rate increases 1% the per mile fleet cost decreases 0.64% in scenario S0. Results with “0.00” elasticity indicate that the absolute value of the elasticity is less than 0.01 or 1/100.

Results show that discount rate, electric truck cost, and vehicle utilization have the highest elasticity (absolute values). The discount rate elasticity decreases with vehicle utilization. On the other hand, the utilization elasticity increases as the vehicles are driven more. Hence, this indicates a non-linear increase in the competitiveness of ECVs as a function of utilization.

Table 5: Parameters Elasticity (whole fleet)

Factors ↓ Scenarios →	S0	S1	S2	S3	S4	S5
<i>General Factors</i>						
Discount rate (4% - 9%)	- 0.64	- 0.60	- 0.54	- 0.58	- 0.46	- 0.45
Low Annual Utilization (11,400mi/yr – 12,600mi/yr)	- 0.20			- 0.49		
Median Annual Utilization (15,200mi/yr – 16,800mi/yr)		- 0.21			- 0.56	
High Annual Utilization (19,000mi/yr – 21,000mi/yr)			- 0.45			- 0.63
CO2 emissions cost (\$19/ton - \$21/ton)	0.00	0.21	0.00	0.00	0.00	0.00
<i>Electric Vehicle Factors</i>						
Electric truck price (\$142,500-\$157,500)	0.00	0.00	0.22	0.16	0.74	0.63
Salvage depreciation rate (10% - 20%)	0.00	0.00	0.00	0.02	0.08	0.06
Electricity price (\$0.10146/kwhr - \$0.11748/kwhr)	0.00	0.00	0.00	0.16	0.00	0.21
Electricity consumption rate (0.76kwhr/mi – 0.84kwhr/mi)	0.00	0.00	0.00	0.16	0.00	0.21
Maintenance cost factor (0.95-1.05)	0.00	0.00	0.00	0.16	0.19	0.21
<i>Diesel Vehicle Factors</i>						
Diesel price (\$3.86/gal - \$4.26/gal)	0.39	0.43	0.22	0.32	0.00	0.21
Fuel inflation rate (0% - 5%)	0.11	0.09	0.07	0.09	0.04	0.03
Diesel truck high MPG (12.787mi/gal – 14.133 mi/gal)	- 0.39	- 0.21	- 0.22			
Diesel truck low MPG (7.79mi/gal – 8.61 mi/gal)				- 0.32	0.00	- 0.21

It is noticeable that the electric vehicle purchase costs have a high elasticity only in the scenarios where electric vehicles are purchased in large numbers. The depreciation rate has a relatively low elasticity. Regarding the parameters affecting the diesel vehicles, diesel price has a high elasticity in scenarios where diesel vehicles are dominant such as S0 and S1.

6. CONCLUSIONS

This research utilizes an optimal fleet replacement framework to find the key economic and technological parameters that affect the competitiveness of electric commercial vehicles (ECVs). This research is primarily focused on evaluating whether electric commercial vehicles, as a new challenger to conventional diesel trucks, are more cost effective than the conventional diesel counterparts.

The presented methodology can be applied to any country or vehicle technologies though the results presented in this research represent 2011 figures for the USA market. The Isuzu N-Series and the Navistar E-Star were selected to represent diesel and electric trucks respectively. Six scenarios were evaluated to reflect demand and operating environment variability between fleets. Results show that when diesel trucks are operated in an environment with 8.2mi/gal (or 13.46mi/gal) fuel efficiency and annual utilization is higher than 14,138 mi/year/truck (or 22,272 mi/year/truck), electric trucks can be more economic competitive than conventional diesel trucks. These annual utilization levels are within a realistic electric vehicle range of battery capacity (54 and 86 miles/day/truck).

Breakeven points and elasticities are calculated to analyze the impact of uncertain or hard to forecast economic or technological parameters. The elasticity and breakeven points of 12 parameters were computed in the six scenarios to understand when electric trucks are more competitive than diesel trucks. The sensitivity analysis results show that a 6 to 12% electric vehicle price reduction can greatly increase their competitiveness when vehicles are driven over 12,000 miles per year. The breakeven point and elasticity of the discount rate (capital costs) indicate the low rates are necessary to ensure the financial viability of electric commercial vehicles. We are currently living period of historically low interest rates; any upward change in interest rates will greatly decrease the competitiveness of electric commercial vehicles. Overall, results show that under good? to high utilization levels, commercial electric vehicles can be competitive. In urban LTL environments. The key barriers to ECV competitiveness seems to be more economical than technological.

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