Electrifying Last Mile Deliveries: The Case of Parcel Delivery Fleets

By

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ABSTRACT

Trucking is a key component of the freight sector, which is an important contributor to the California economy, but also contributes to externalities associated with climate and local emissions, congestion, and noise, among others. Last mile distribution relies on the trucking sector to connect the final receiver with the rest of the supply chain. Growing demand for goods and services in urban and residential areas requires sustainable freight transportation alternatives. Electric trucks have become a feasible alternative to improve last mile deliveries, but their additional cost and operational barriers hinder their deployment and widespread adoption.

This work assesses alternative technologies using real driving data for parcel delivery fleets and evaluates the role of monetary incentives in California. The analyses show that electric trucks are a technically feasible and the cleanest alternative in California in terms of petroleum use, greenhouse gases (GHGs) and air pollutants; however, they require economic incentives to support a transition to a cleaner freight transportation system.

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1. INTRODUCTION

The freight transportation sector is an important contributor to the economy. In 2013, it accounted for almost one third of California's jobs and economy (California Governor's Office, 2016). In 2015, freight transportation moved $19.1 trillion (2012 USD) worth of goods across the United States, with on-road transport representing the largest share both in weight and tonnage (U.S. Department of Transportation & Statistics, 2018). Not surprisingly, on-road transportation dominates goods movement because trucking is required at some point along the supply chain; especially, for the goods that have an urban area destination, trucking is mostly the only option. In Southern California, 85% of the truck traffic in the region are internal trips and deliveries despite of having the largest U.S. ports (Port of Los Angeles and Long Beach) in the country (SCAG, 2016).

Moreover, recent changes in supply chain management and operations, and rising home deliveries due to online shopping and the on-demand economy (UPS, 2016) have exacerbated the challenges in the logistics of last mile distribution. Although these trends and others will continue to affect the freight system, truck traffic today is generating congestion and is responsible for a great share of transport externalities. Although passenger vehicles generate approximately five times more GHGs emissions and consume most of the fuel used in the California transportation sector (CARB, 2017), heavy-duty vehicles, which comprise a small fraction of the transportation fleet, contribute an outsized portion of local air emissions. For example, in 2015 medium- and heavy-duty vehicles comprise only about one million of the 30 million registered vehicles in California (CEC, 2018), but they are the largest nitrogen oxides (NOx) emission source from the transportation sector.

The U.S. and California have implemented different regulations and policies to reduce the emissions from HDVs, focusing on alternative fuels, tailpipe emissions controls, and energy efficient technologies. Specifically, the California Sustainable Freight Action Plan set the following goals: 1) improve freight system efficiency measured by the relationship between the economic contribution of some freight industries and the generated environmental emissions; 2) introduce zero and near-zero emission vehicles and equipment; and 3) improve its economic competitiveness (California Governor's Office, 2016). But there are several economic, financial, technological, operational, and behavioral challenges to achieve these goals. Fostering the use of zero and near-zero emission vehicles must address the fact that the companies and supply chains in the system have different fleet ownership, operations, and finance models. Also, vehicles have different uses throughout their lifetimes, and their drivetrain configurations may only fit a specific vocation.

Considering the growing importance of last mile distribution and how freight delivery vehicles are serving even more densely populated areas (compared to long-haul transport), this work looks at last mile operation of delivery fleets and it evaluates the life cycle assessment (LCA) and total cost of ownership (TCO) of different drivetrain technologies for parcel fleets using real driving data.

2. VEHICLE TECHNOLOGIES

The main drivetrains and fuels currently available in the market for medium- and heavy-duty trucks (with limited applications for different vocations) are conventional diesel and gasoline (for smaller weight classes), biofuels, hybrid-electric (HEV), natural gas, battery-electric (BEV) and hydrogen fuel cell (IEA, 2017).

All of these technologies offer different energy efficiencies, infrastructure and operational costs, GHG and criteria pollutant emissions which can be suitable for specific vocations and drive cycles.

Researchers have investigated the application of near zero- and zero-emission vehicles in different freight vocations using general modeling schemes and optimizations methodologies (Ang-Olson & Schroeer, 2002; Bachmann, Chingcuanco, MacLean, & Roorda, 2014; Demir, Bektaş, & Laporte, 2011, 2014; Den Boer, Aarnink, Kleiner, & Pagenkopf, 2013; Hackney &

De Neufville, 2001; D.-Y. Lee, Thomas, & Brown, 2013; G. Lee et al., 2009; Hans Quak & Nesterova, 2014; Zanni & Bristow, 2010).

Regarding last mile deliveries, Bachmann et al. (2014) analyzed urban delivery trucks operations in Canada by comparing diesel and HEV drivetrains with an LCA model. They show CO_2 emission reductions of 25% by using HEVs. Similarly, D.-Y. Lee et al. (2013) performed an LCA of BEVs for urban deliveries estimating the energy and fuel use, emissions and TCO for different drive cycles. Electric trucks have overall less emissions and have a close TCO compared to their diesel counterparts, but the results are sensitive to the efficiency of the vehicle, fuel and energy prices, vehicle miles traveled (VMT), battery replacement, charging infrastructure, electricity production and purchase price.

In Europe, as part of the Freight Electric Vehicles in Urban Europe (FREVUE) project (European Union, 2016), Hans Quak, Nesterova, and van Rooijen (2016); Hans Quak, Nesterova, van Rooijen, and Dong (2016) analyzed a number of case studies that include approximately 100 zero-emission vehicles from demonstration projects in participating cities in the Netherlands, Norway, Spain, Portugal, and the United Kingdom. In Lisbon, electric vehicles proved to be a suitable substitute technology from diesel drivetrains that allowed the operation of the same routes. Moreover, the total cost per kilometer was equal for both technologies already accounting for the additional purchase price of the electric vehicle, since reduced operational costs from fuel and maintenance offset the additional purchase costs (Duarte, Rolim, & Baptista, 2016).

Feng and Figliozzi (2012) developed a fleet replacement framework comparing two diesel and electric trucks available commercially. Their results show that higher VMT (~16,000 miles per year) and reduction in electric purchase price (9-27%) leads to higher competitiveness of electric vehicles. But other factors like discount rate and lifetime of trucks have an important impact on the results. Driving cycles impact the fuel efficiency of the vehicles, in particular lower speeds are suitable for electric drivetrains. For parcel delivery vehicles (class 3 and 5) energy efficiency rates of 4.8 to 6.9 for electric trucks were found in in-use data compared to conventional diesel trucks, in other words, electric trucks were 5 to 7 times more efficient (CARB, 2018).

CalHEAT and CALSTART (2013) show the results of a pilot for parcel delivery vocations comparing electric versus diesel trucks using on-road and dynamometer testing. The outcome shows that electric trucks are 4 times more energy efficient per mile and cheaper to operate than conventional diesel vehicles overall, although the drive cycle impacts the performance of these vehicles. In general, fuel costs of electric trucks were about 20% of those of conventional diesel vehicles, regenerative breaking rates can reach up to 37%, and emissions using California electricity grid reduced by 70% of GHGs on a well to wheels (WTW) basis.

Vehicle technologies can improve the performance of trucks as demonstrated in recent studies and pilots for near zero- and zero-emission vehicles that show reductions in emissions, noise, energy, and fuel consumption.

Table 1 compares the efficiency between diesel, HEV and BEV trucks for different pilot tests that assessed the energy consumption and costs of operating these technologies. The scope of these studies is not a life cycle but rather direct measurements of in-use data through on-road or dynamometer testing.

Table 1 Pilot tests for delivery trucks

MPG (DGE)*	Diesel	HEV	BEV	Details	Source
Class 3	11.2		76.8	CAlHEAT- Navistar eStar In-Use Route	(CARB, 2018)
			46.1	Navistar eStar	(Giuliano, White, & Dexter, 2018)
Class 4	10.6	13		Thirty-Six Month Evaluation of UPS Diesel Hybrid-Electric Delivery Vans - 2012	(M. Lammert & Walkowicz, 2012b)
	10.2	13.1		UPS Hybrid Electric Delivery Vans - 2010	(M Lammert, 2009)
Class 5	11.7		56.2	CAlHEAT- HTUF4 - Test Cycle	(CARB, 2018)
	9.5		52.3	CAlHEAT- OCBC - Test Cycle	(CARB, 2018)
Class 6	9.2	10.4		UPS Hybrid Electric Delivery Vans - 2012	(M. Lammert & Walkowicz, 2012a)

	7.9	9.4		UPS Hybrid Electric Delivery Vans - 2013	(M. Lammert & Walkowicz, 2012a)
	8.8	10		UPS Hybrid Electric Delivery Vans - 2014	(M. Lammert & Walkowicz, 2012a)
			24.9	Smith Newton Trucks	(Giuliano et al., 2018)
Class 7	10.7		30.6	FREVUE 2017	(H. Quak, Koffrie, Van Rooijen, & Nesterova, 2017)
*MPG = miles per gallon, DGE = diesel gallon equivalent					

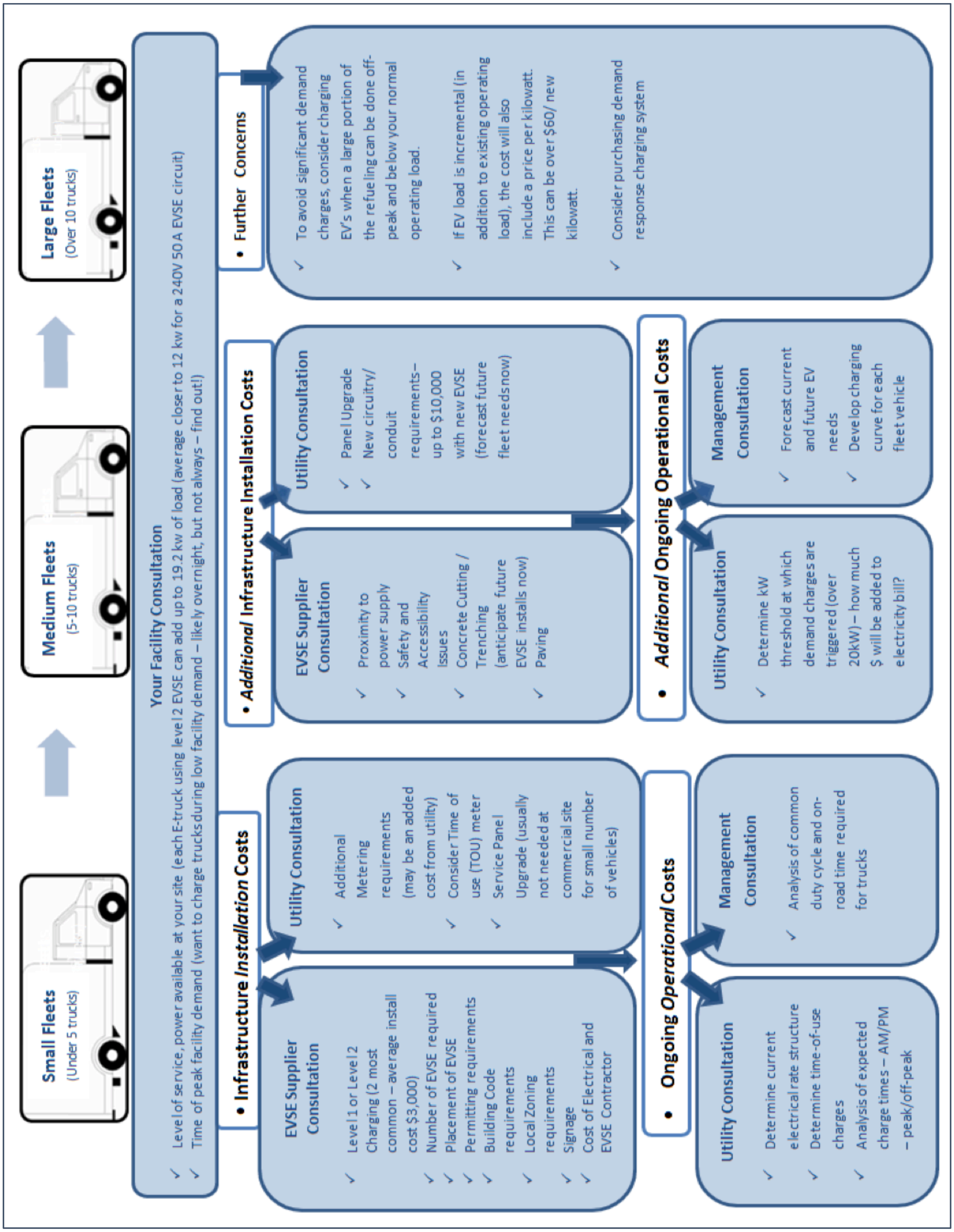
2.1. Battery electric trucks

Many of the pilot projects and studies implementing zero-emission technologies focus on electric technologies due to the readiness of the vehicle technology and associated infrastructure. Available incentives in California for purchase price and electricity generation also make BEVs a feasible solution for passenger vehicles and trucks (See 2.2).

Similar to passenger electric vehicles, current electric trucks' operational limitations of limited range, refueling time, infrastructure investments, and purchase price have hindered their general adoption in commercial fleets. Truck drivers also experience "range anxiety" derived from uncertainties about the true range of a vehicle and are constrained to specific routes and destinations where available charging, fueling, or reloading infrastructure exists (Davis & Figliozzi, 2013; Feng & Figliozzi, 2012).

Therefore, an important aspect to consider for operating electric fleets is charging infrastructure or electric vehicle supply equipment (EVSE) installation and operation which relates to grid upgrades, landlord permits, charging time per vehicle, infrastructure and vehicle operation and maintenance (Hans Quak, Nesterova, & van Rooijen, 2016; Hans Quak, Nesterova, van Rooijen, et al., 2016). In general, there are four charging strategies: home/depot-charging; public charging, inductive charging, and battery replacement. Charging time is unique for the fleet characteristics in terms of their battery characteristics and size, use of battery over time (charge and discharge), and EVSE infrastructure (Hans Quak, Nesterova, & van Rooijen, 2016; Hans Quak, Nesterova, van Rooijen, et al., 2016). In the FREVUE tests, participating companies revealed that depot-charging was a suitable option for their fleets but one charger per vehicle was required, which implied additional infrastructure investments. Charging operations were performed overnight as along with other operation activities such as maintenance (Hans Quak, Nesterova, & van Rooijen, 2016; Hans Quak, Nesterova, van Rooijen, et al., 2016).

CalHEAT and CALSTART (2013) developed some EVSE guidelines based on the size of the fleet that provide additional information on considerations when switching to BEV trucks (**Error! Reference source not found.**).



Source: (CalHEAT & CALSTART, 2013)

Figure 1 Infrastructure planning guidelines for BEV truck fleets

By the end of May 2018, as part of the implementation of the Senate Bill 350 *Clean Energy and Pollution Reduction Act,* a pool of transportation electrifications projects worth $730 million were approved. PG&E, SDG&E and SCE[1] filed their proposals, which encompass "make-ready" services and chargers. Make-ready services refer to the connection and supply infrastructure required to/from the grid distribution such as transformers or electrical installation. Many BEV projects fail to consider make-ready services in advance, which can significantly impact the total cost of ownership of an electric fleet. The projects proposed by the utilities derived from SB 350 will support the electrification of fleets at relevant locations (e.g., transit depots, warehouses)[2].

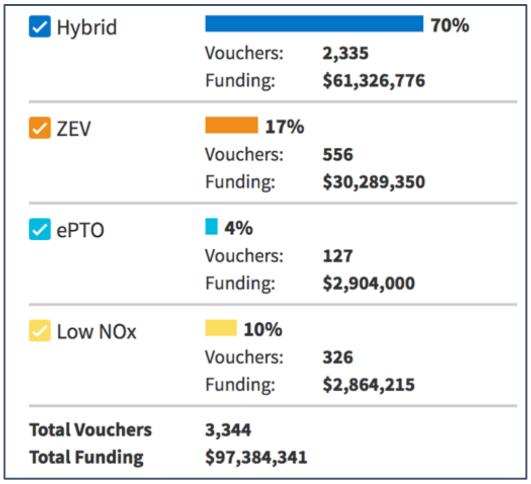
2.2. Monetary incentives

The higher cost of electric technologies remains as one of the barriers to adopt them. In California, the Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project (HVIP) provides voucher incentives applicable directly to the cost of the truck for eligible alternative technologies (CARB & CALTRANS, 2018). Eligible technologies under the HVIP program are: battery-electric, fuel cell, hybrid and ultra-low NOx natural gas engines. The voucher varies by technologies, from approximately $2,500 to $100,000; battery-electric and fuel-cell trucks receive the highest incentive amounts. As of July 1, 2018, 3,344 vehicle purchases used the incentive program and around $110 million are still available. At least 35% of the funds of the program are to be spent in disadvantaged and low-income communities. Most of the vouchers have been used to purchase hybrid vehicles (70%), followed by zero-emission vouchers for fuel-cell and battery-electric vehicles.

Table 2 HVIP voucher results

[1] Pacific Gas and Electric Company (PG&E), San Diego Gas & Electric Company (SDG&E), and Southern California Edison Company (SCE)

[2] http://www.cpuc.ca.gov/sb350te/



Source: (CARB & CALTRANS, 2018)

3. METHODOLOGY

This study uses publicly available information from the Fleet DNA project –Commercial Fleet Vehicle Operating Data– of the National Renewable Energy Laboratory (NREL) (K. Walkowicz, Kelly, Duran, & Burton, 2014). Fleet DNA is a composite of driving data for medium- and heavy-duty commercial vehicles within weight classes 2 to 8. It includes information about the operation of different truck technologies but due to data confidentiality, the name of the companies, the location of the vehicles and their technical specifications are not disclosed. The information includes 4,705 days of data points related to number of stops and trips, speed, acceleration, daily travel distance, fuel and drivetrain type, tour and trip duration, among other variables. Out of the 16 vocations identified in the original dataset, just a few have information and from those, the most complete subgroup is parcel delivery. Consequently, the final dataset used in this work comprised of just parcel delivery vocation which had almost 700 days of information for 79 vehicles of conventional diesel, parallel-and hydraulic-hybrid drivetrains. The data is aggregated under the two service providers or companies (PID 3 and PID 16). The data does not include fuel consumption information, but it was estimated using the specific fuel consumption or SFC (O'Keefe, Simpson, Kelly, and Pedersen (2007), Ambrose (2017), (Gao & Pineda, 2017)) that allows calculation of the fuel consumption of a vehicle when there is no standardized representative drive cycle. It uses variables such as the characteristic acceleration which is a measure of a cycle's acceleration and grade intensity; aerodynamic speed which is the ratio of the average cubic speed to the average speed of a cycle; and other characteristics of the vehicle operation. Knowing the fuel economy information of each truck allows the comparison of their fuel consumption and its consideration in the TCO analysis.

For the TCO analyses, the California Alternative Fuel Life-Cycle Environmental and Economic Transportation (AFLEET 2017) tool was used. AFLEET 2017 estimates energy use, GHGs, air pollutants and TCO for alternative fuel and vehicle technologies. It builds on the Greenhouse gases, Regulated Emissions, and Energy use in Transportation Model (GREET 2016) model to generate well-to-wheels analysis for the fuel cycle, excluding vehicle manufacturing (only available for passenger vehicles), and the Environmental Protection Agency's Motor Vehicle Emission Simulator (MOVES) to estimate tailpipe emissions. The tool uses several data sources for its costs estimates that are documented in "User guide for AFLEET Tool 2017" and in the "Background Data" tab of the AFLEET 2017 spreadsheet tool (K. Walkowicz, Kelly, Duran, & Burton, 2014).

The methodology applied to analyze the data and characterize last mile delivery operations for parcel delivery comprises these main steps:

1. Descriptive and comparative analyses of parcel delivery with other delivery vocations to identify travel patterns and drive cycles. This accounted for the differences on drivetrain technologies and vehicle weight class.
2. Cumulative tour length distributions (TLDs) of daily vehicles miles traveled (DVMT) and specific fuel consumption (SFC) estimation. TLDs allow for a better comparison between vocations in terms of DVMT and to identify the minimum range required by a vehicle to fulfill most of their operations as in their cumulative functions. SFC is used as an input to the model for the overall operation of the vehicles.

3. The assessment of TCO and LCA of the two fleets from Fleet DNA are evaluated under several fuel technologies[3] using AFLEET 2017. In order to compare both providers it was assumed the same proportion of vehicles by class and drivetrain for two 100-vehicles fleet that would represent each company using their specific characteristics, i.e. miles traveled and fuel consumption.
4. Finally, a sensitivity analysis for electric trucks to show the main factors that affect the TCO and the effectiveness of financial incentives.

General assumptions and scenarios

The TCO and LCA assessment is based on AFLEET 2017, and thus the assumptions are consistent with its methodology. Some general inputs (e.g., fuel and energy prices) were updated for all analyses and other parameters are specific to each scenario.

AFLEET 2017 incorporates several drivetrain technologies but some of them are not available for certain classes or vocations. This study shows the results for the following technologies: diesel (including renewable and biodiesel), diesel HEV, BEV and natural gas (CNG, LNG) vehicles. Fuel prices, annual VMT and fuel economy values for all the analyses were revised and updated. For example, fuel prices were updated as of April 2018 keeping consistency with the sources used in AFLEET 2017. Fuel economy for the different truck classes was updated with the calculated SFC and their annual VMT[4] was computed using their average DVMT. Fuel prices[5] and grid composition reflect West Coast or California conditions since the goal is to model the case of fleets operating in California, accounting for the incentives available in the region.

For AFLEET 2017 emissions output, the analyses used the "*Well-to-Wheels Petroleum Use, GHGs, and Air Pollutants*" calculation to account for a more comprehensive environmental

[3] Conventional diesel including biodiesel and renewable diesel, HEV, BEV, and natural gas for CNG and LNG.

[4] Based on the daily VMT obtained from the fleets, and assumed to drive 312 days a year.

[5] Premium reformulated gasoline and ultra-low sulfur diesel

impact. Specifically, San Francisco, California was chosen to reflect the effect on local air pollutants and the "*Diesel In-Use Emissions Multiplier*" option was not used. The air pollutants from well-to-pump and vehicle operation considered in AFLEET 2017 are carbon monoxide (CO), particulate matter ($PM_{2.5}$ and PM_{10}), volatile organic compounds (VOC), nitrogen oxides (NO_x) and sulfur oxides (SO_x). AFLEET 2017 TCO results include the quantification of petroleum use, GHGs and air pollutants as externalities.

Considering the uncertainty and variation of the different variables resulting from the empirical parcel data and the results of the pilot studies and other research, three main modeling scenarios are considered. These scenarios also account for financial incentives and infrastructure costs. The scenarios vary in several parameters: a) the energy efficiency ratio (EER) of electric vehicles compared to their diesel counterparts. The EER default value in AFLEET 2017 is 2.55. The first scenario or scenario 0, considers this value. The other 2 scenarios, scenario 1 and 2 increase this factor based on pilot tests and OEM information for different truck classes, and use 4.8 and 5.7 EERs, respectively. b) The scenarios with improved EER for electric trucks also consider Low NOx engines for CNG and LNG. These scenarios do not consider financial voucher incentives for CNG and LNG vehicles, because there is uncertainty about the price increase of those vehicles. And, c) The use of vehicle purchase incentives from the HVIP program and fuel credits from the Low Carbon Fuel Standard (LCFS) in California (CARB & CALTRANS, 2018). The analyses use a LCFS credit of $0.07/kWh based on a $120 credit price, as an average in April 2018. The resulting scenarios are as follows:

- Scenario 0: Default EER (2.55)
    - Scenario 0 + LCFS
    - Scenario 0 + HVIP
    - Scenario 0 + LCFS + HVIP
- Scenario 1: Improved EER (4.8) + Low NOx CNG/LNG
    - Scenario 1 + LCFS

- Scenario 1 + HVIP
- Scenario 1 + LCFS + HVIP

- Scenario 2: Improved EER (5.7) + Low NOx CNG/LNG
  - Scenario 2 + LCFS
  - Scenario 2 + HVIP
  - Scenario 2 + LCFS + HVIP

Truck classifications

AFLEET 2017 uses MOVES truck classifications which are based on several characteristics of use, vocation, and size (i.e., utility cargo van, delivery step van, deliver straight truck, regional haul freight truck). However, to be consistent with the Federal Highway Administration (FHWA) vehicle classes (e.g., class 3, 4, 5, … ,8), the AFLEET 2017 categories were combined and averaged to create specific classes to reflect the FHWA vehicle class based on their gross weight vehicle rating (GWVR). Therefore, classes 3 and 5 result from averaging the 2 vehicle categories that overlap based on MOVES classification, classes 4, 6 and 7 refer to a single category used in the AFLEET tool.

- Class 3 = Utility Cargo Van + Delivery Step Van (average)
- Class 4 = Delivery Step Van
- Class 5 = Delivery Step Van + Delivery Straight Truck (average)
- Class 6 = Delivery Straight Truck
- Class 7 = Regional Haul Freight Truck

Purchase price, maintenance costs and incentives

The default purchase prices suggested in AFLEET 2017 were used because they were consistent with market data and information collected from brochures and websites from different manufacturers. This is the same case for maintenance costs that were consistent with data provided by an OEM, therefore default values in the tool were kept. For class 3 and

5 vehicles, which required combining two truck types, the average of their default values was used. The analyses consider the purchase incentives from HVIP for BEV and HEV trucks to calculate the TCO for the different technologies. Incentives for BEV go from $50,000 for class 4, $80,000 for class 5 and 6 and $90,000 for class 7; in the case of class 3, the analyses do not consider incentives because for lighter trucks the vouchers are approved on a case-by-case basis when the companies demonstrate they have a commercial use. For HEV vehicles, a class 3 voucher is $6,000 and for classes 4, 5 and 6 is $15,000.

As discussed before, the European pilot projects highlighted the need for a one-to-one relationship between the number of vehicles and the number of chargers for electric vehicles. But this could also be considered a conservative assumption since many chargers could be optimized and serve multiple trucks.

Moreover, considering that the actual delivery distances are within the ranges of most vehicle technologies (as shown in the **EMPIRICAL RESULTS** section), the analyses assume that the refueling or charging infrastructure would be required at the company's facility.

Since the analyses of both companies are based on a 100-vehicle fleet comparison, the study also examined each truck class under the same scenarios to better understand the outcome at the aggregated level. The breakdown of each fleet composition is shown in Table 3.

Table 3 Vehicle composition by parcel delivery fleet

Class	**3**	**4**		**5**		**6**		**7**		**Total**
Drivetrain*	**0**	**0**	**1**	**0**	**1**	**0**	**1**	**0**	**1**	
PID 3	7	1	9	3	9			9	1	39
PID 16		11	15			8	6			40

* Drivetrain 0 = diesel, 1 = hybrid (parallel or hydraulic)

Table 4 shows a summary of some model parameters for diesel, HEV and BEV trucks used in the assessment.

Table 4 Model parameters for diesel and BEV trucks

	Purchase Price		**HVIP incentive**		**Annual VMT**		
	Diesel	BEV	BEV	HEV	AFLEET	PID 3	PID 16
Class 3	$ 55,750	$ 107,250	0	6,000	21,750	18,096	
Class 4	$ 65,000	$ 145,000	50,000	15,000	16,500	12,380	17,898
Class 5	$ 70,000	$ 167,500	80,000	15,000	19,750	13,098	
Class 6	$ 75,000	$ 190,000	80,000	15,000	23,000		11,044
Class 7	$ 90,000	$ 290,000	90,000	0	65,000	8,809	

	Maintenance and repair ($/mile)		**Fuel economy (miles per diesel gallon equivalent)**				
	Diesel	BEV	AFLEET Diesel	AFLEET BEV	PID3 Diesel	PID16 Diesel	
Class 3	$ 0.256	$ 0.177	10.6	27.1	13.9		
Class 4	$ 0.201	$ 0.139	7.4	18.9	10.9	13.4	
Class 5	$ 0.203	$ 0.151	7.0	17.8	9.8		
Class 6	$ 0.204	$ 0.162	6.6	16.7	0	8.1	
Class 7	$ 0.190	$ 0.173	7.4	18.9	8.0		

4. EMPIRICAL RESULTS

4.1. Delivery fleets

Table 5 shows summary statistics for all delivery vocations, beverage, warehouse, parcel, linen, food, local and parcel from Fleet DNA. Let's recall that these vehicles are only diesel drivetrains, i.e. conventional diesel, parallel- and hydraulic-hybrid. Parcel has the shortest DVMT. Local deliveries travel almost three times more than parcel and surpass warehouse and food delivery.

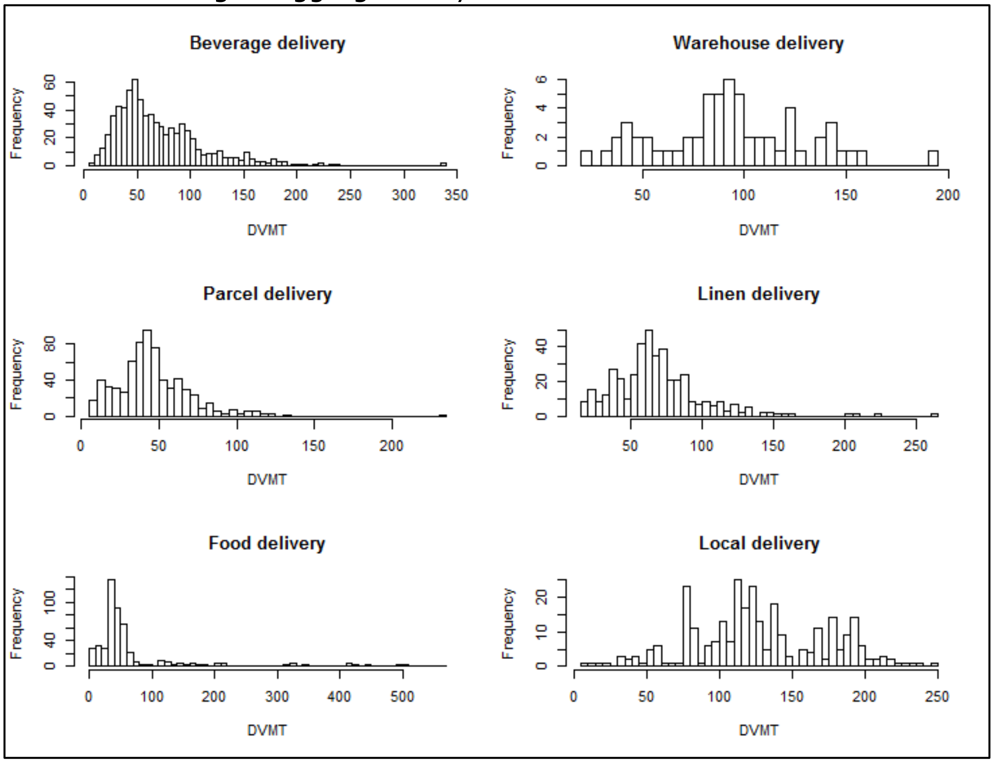
Table 5 Summary statistics for DVMT by vocation (miles)

Vocation	Min.	Median	Mean	Max.
Beverage	7.132	58.7	70.56	339.2
Warehouse	20.92	91.67	93.02	191.5
Parcel	5.638	42.82	45.42	231.8
Linen	15.04	64.45	68.14	261.7
Food	5.128	41.23	73.49	568.3
Local	9.439	123.3	127.3	248.9
All delivery	5.128	54.48	70.96	568.3

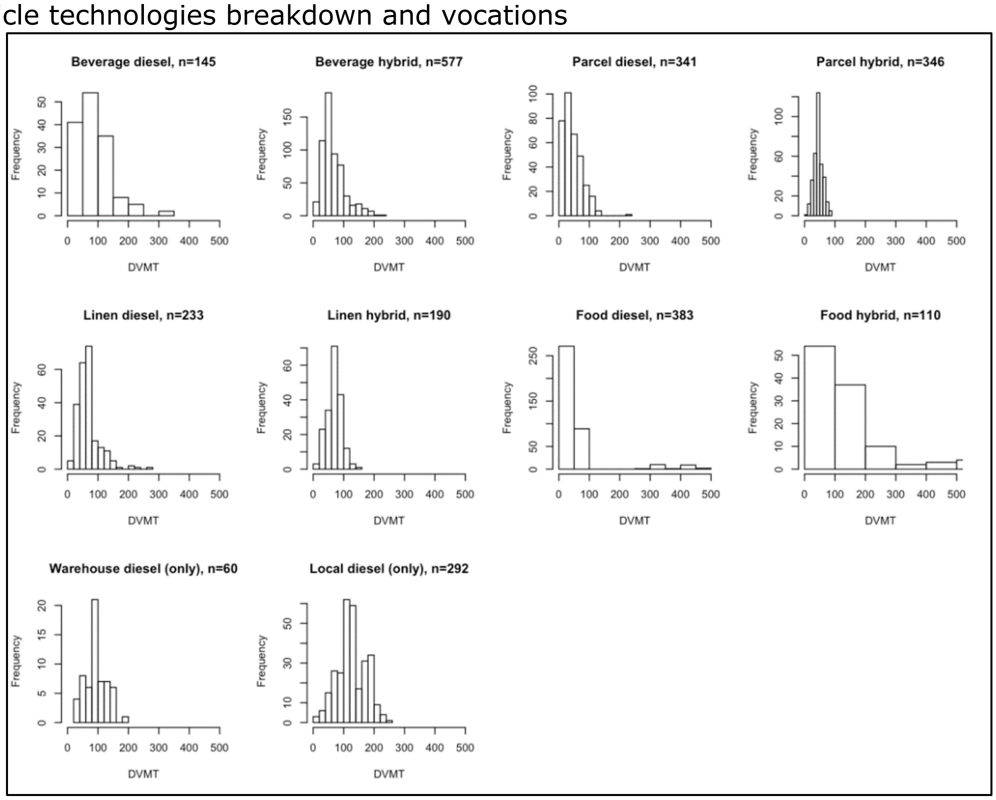
Source: Own with information from Fleet DNA (K. K. Walkowicz, K.; Duran, A.; Burton, E, 2014)

Error! Reference source not found. shows the distribution of the DVMT for the different vocations. Beverage, parcel, linen, and food exhibit the highest concentrations below 100 miles, while warehouse delivery and local have a significant proportion of daily routes exceeding this threshold using only conventional diesel vehicles (see Part a). This figure also shows that the companies are using some of the vehicle technologies differently; for example, parcel vocations use conventional trucks across various daily operations, but they seem to use hybrids for those daily routes that do not exceed 100 miles. On the contrary, the empirical data shows that food deliveries use hybrid vehicles for much longer routes. Within a 100-mile distance, beverage, linen, food, and parcel delivery routes represent more than 80% of the routes in the sample with parcel having more than 95% of routes below this level, supporting electrification with current technologies (**Error! Reference source not found.**).

2a. All vehicles technologies aggregated by vocation

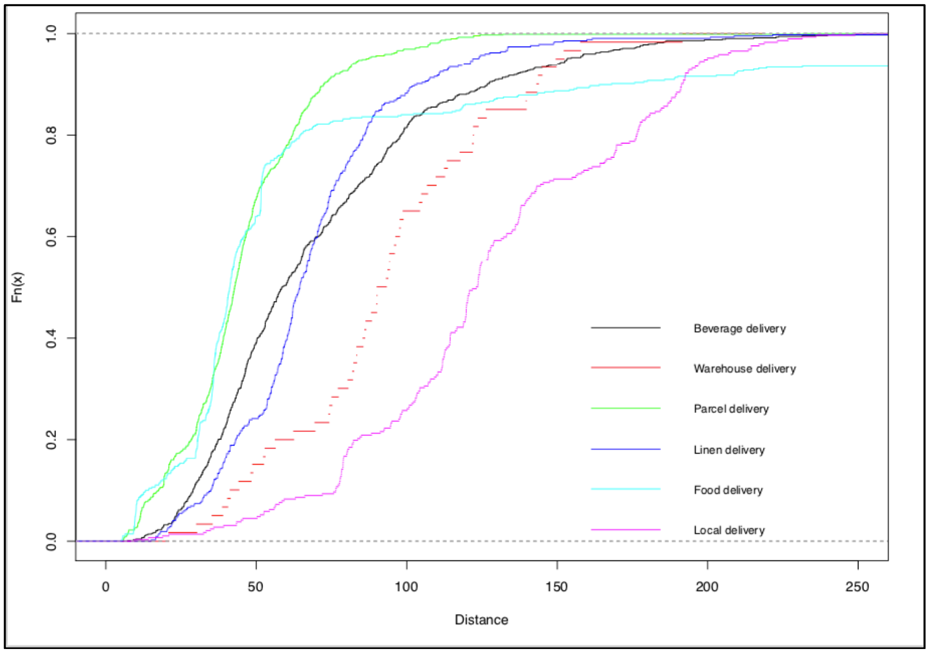


2b. Vehicle technologies breakdown and vocations



Source: Own with information from Fleet DNA (K. K. Walkowicz, K.; Duran, A.; Burton, E, 2014)

Figure 2 Daily vehicle miles traveled (DVMT) for last mile delivery vocations



Source: Own with information from Fleet DNA (K. K. Walkowicz, K.; Duran, A.; Burton, E, 2014)

Figure 3 Cumulative vehicle miles traveled distances per vocation

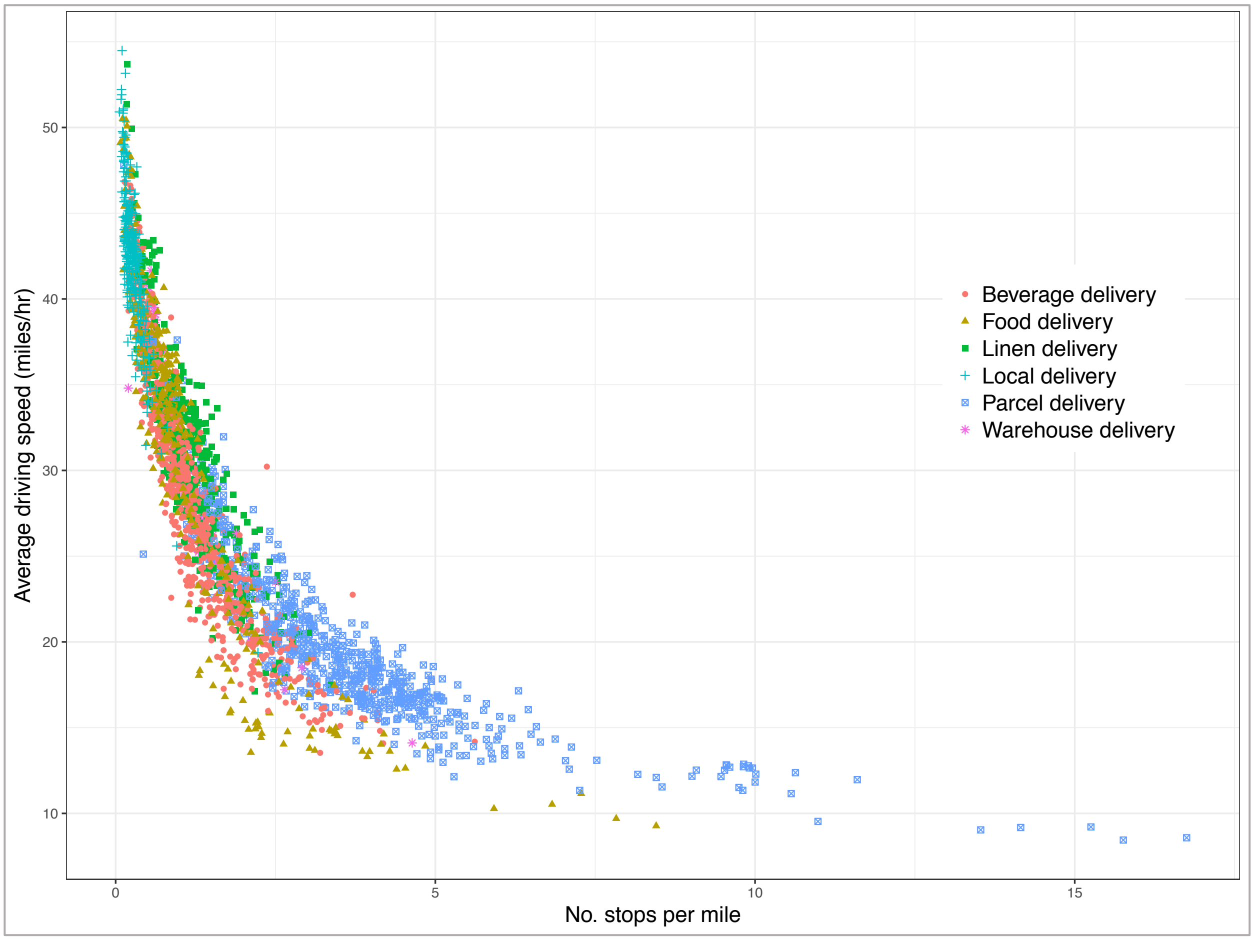
From the previous results, parcel delivery concentrates its operations under a 100-mile range. But looking at other variables characteristic of last mile distribution, i.e., high number of stops and low average speeds, parcel vocation is consistent with urban driving cycles standing out by having shorter trips, higher number of stops, and lower driving average speeds, compared to other delivery vocations (Table 6 and

).

Table 6 Travel patterns of parcel and delivery vocations

	Category	Min.	1st. Quartile	Median	Mean	3rd. Quartile	Max.
DVMT	Parcel	5.638	31.46	42.82	45.42	57.56	231.8
	All delivery	5.128	37.89	54.48	70.96	86.42	568.3
Total stops	Parcel	3	106	159	143.8	188	284
	All delivery	3	37	67	81.14	106	284
Stops/mile	Parcel	0.1276	2.341	3.266	3.56	4.381	16.75
	All delivery	0.05881	0.6235	1.209	1.721	2.318	16.75
Avg. speed	Parcel	8.447	16.81	18.99	20	22.81	47.84
	All delivery	0.447	20.95	28.61	28.84	35.63	54.48

Source: Own with information from Fleet DNA (K. K. Walkowicz, K.; Duran, A.; Burton, E, 2014)



Source: Own with information from Fleet DNA (K. K. Walkowicz, K.; Duran, A.; Burton, E, 2014)

Figure 4 Stops per mile and average speed for delivery vocations

4.2. Parcel Deliveries

The results show that the heavier the vehicle the lower the miles per gallon (mpg), with values ranging from 8 to 13.9 mpg. In terms of fuel efficiency, class 3 has the highest mpg, class 4 is approximately 5% less efficient, class 5 is 30% less efficient, and classes 6 and 7 are about 40% less efficient, all compared to class 3. The data shows that hybrid vehicles efficiency over conventional vehicles is between 1% and 20% (class 4 = 0.57%, class 5 = 11.39%, class 6 = 22.84% and class 7 = 5.92%). Class 6 hybrids are the only hydraulic hybrid technology in both fleets, the rest of hybrid vehicles in other classes have a parallel configuration. The results may suggest that hydraulic hybrid vehicles have a better efficiency than parallel hybrids, although there is not sufficient information to support this hypothesis.

See summary statistics in Table 7.

Table 7 Summary statistics for parcel deliveries from different service providers

	Class	**3**	**4**		**5**		**6**		**7**	
	Drivetrain	0	0	1	0	1	0	1	0	1
Company 1 (PID=3)	Number of days of data:	92.0	6.0	49.0	19.0	112.0			104.0	13.0
	Minimum DVMT (mi):	19.3	5.9	12.5	18.9	12.9			6.3	14.8
	Average DVMT (mi):	58.0	24.0	41.6	43.4	41.7			27.0	38.2
	Maximum DVMT (mi):	112.9	37.5	72.2	96.6	77.9			85.2	74.8
	Standard Deviation DVMT (mi):	21.6	14.4	13.7	14.7	9.6			15.5	15.9
	Average speed (mph)	20.3	23.6	17.6	17.4	19.0			25.2	27.1
Company 2 (PID=16)	Number of days of data:		73.0	134.0			47.0	38.0		
	Minimum DVMT (mi):		21.0	9.5			5.6	14.1		
	Average DVMT (mi):		70.2	50.4			26.1	46.9		
	Maximum DVMT (mi):		231.8	83.1			74.2	88.3		
	Standard Deviation DVMT (mi):		36.5	15.2			21.0	19.1		
	Average speed (mph)		22.6	18.3			14.9	16.6		
All	Average DVMT	58	66.7	48.0	43.4	41.7	26.1		27.0	38.2
	Average MPG	13.9	13.2	13.3	9.8	10.9	8.1	10.0	8.0	8.4

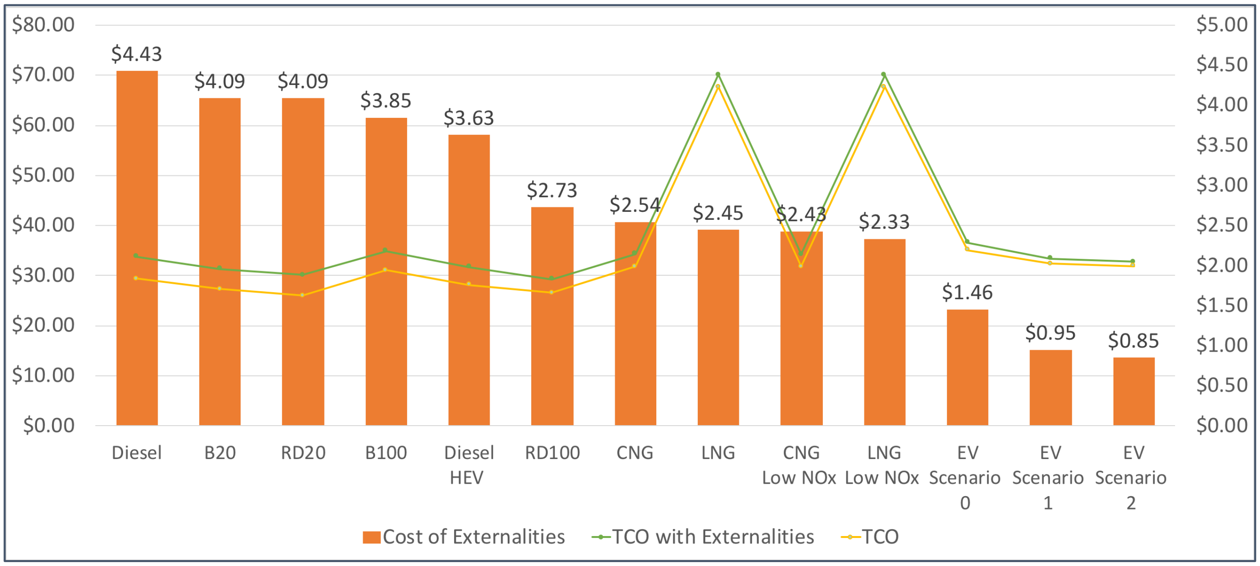
Note: Drivetrain 0 = Conventional, 1 = Hybrid (parallel or hydraulic); DVMT: Daily vehicle miles traveled

4.3. Fleet assessment: TCO and LCA

Nine scenarios (as described in the **METHODOLOGY** section) were evaluated and they include monetary incentives and energy efficiency improvements to compare electric trucks with conventional diesel trucks and other alternative fuels and powertrains.

Hydrogen fuel-cell vehicles were originally considered in the assessment since they are part of the technologies available in AFLEET 2017, but the model did not show results for all truck classes of this technology making it not possible to assess the aggregated impact for both of the fleets, therefore fuel cell drivetrains are not included in this analysis.

The results show that BEVs have the lowest cost of externalities, making them the cleanest technology option for both fleets (**Error! Reference source not found.** and Figure 5 *TCO and externalities for fleet provider 3*



). Electricity production assumes the emissions and grid of the WECC market, thus the results could be different in other regions of the U.S. where less clean electricity production makes up the supply.

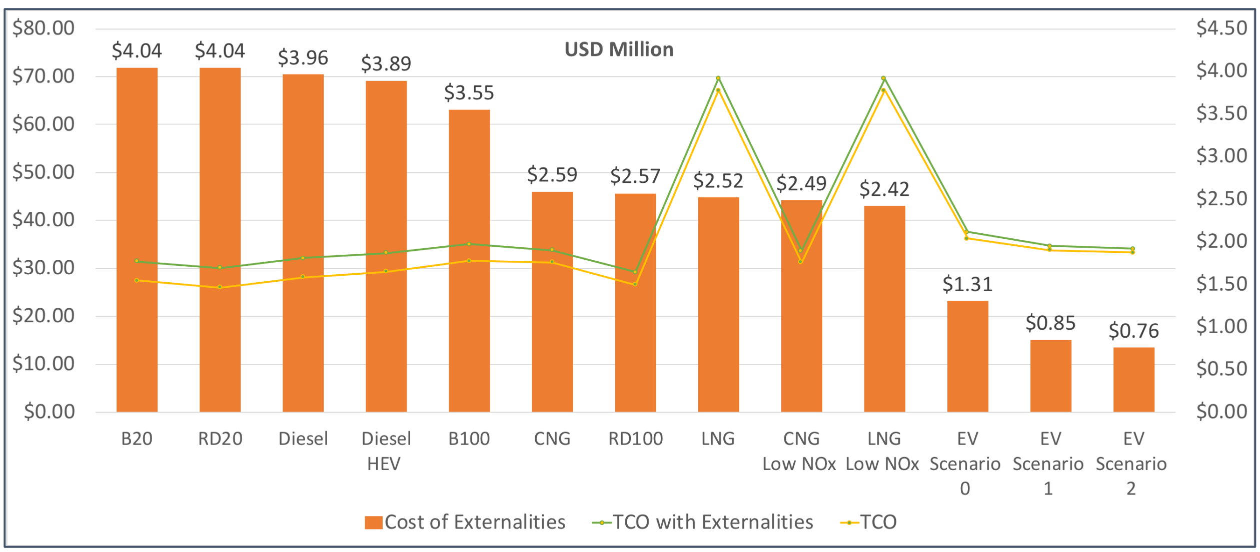


Figure 5 TCO and externalities for fleet provider 3

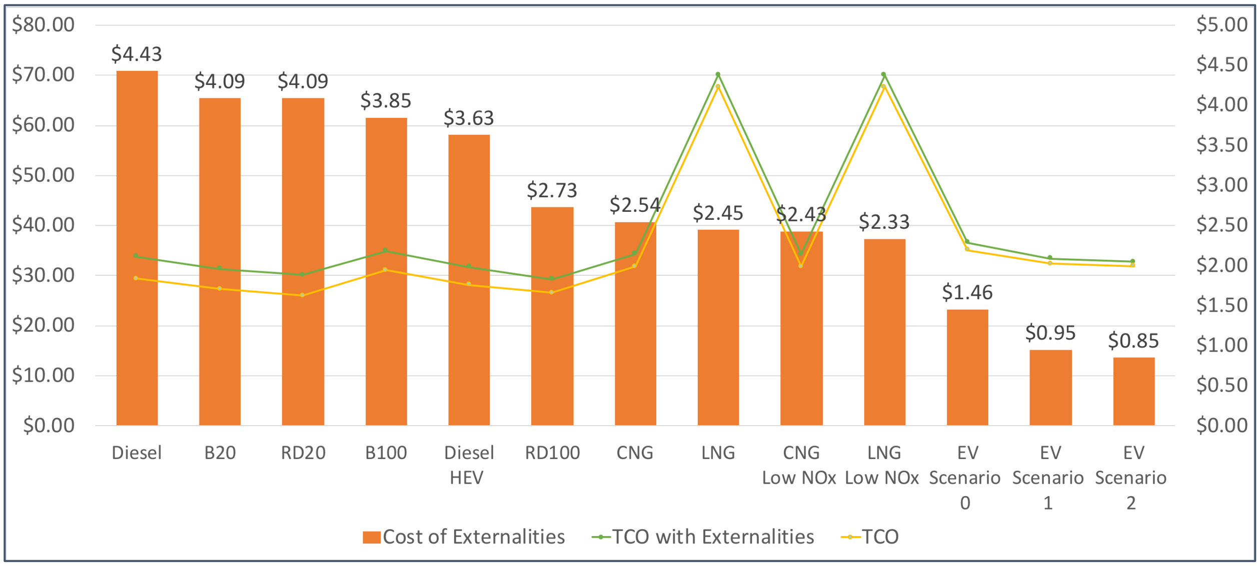
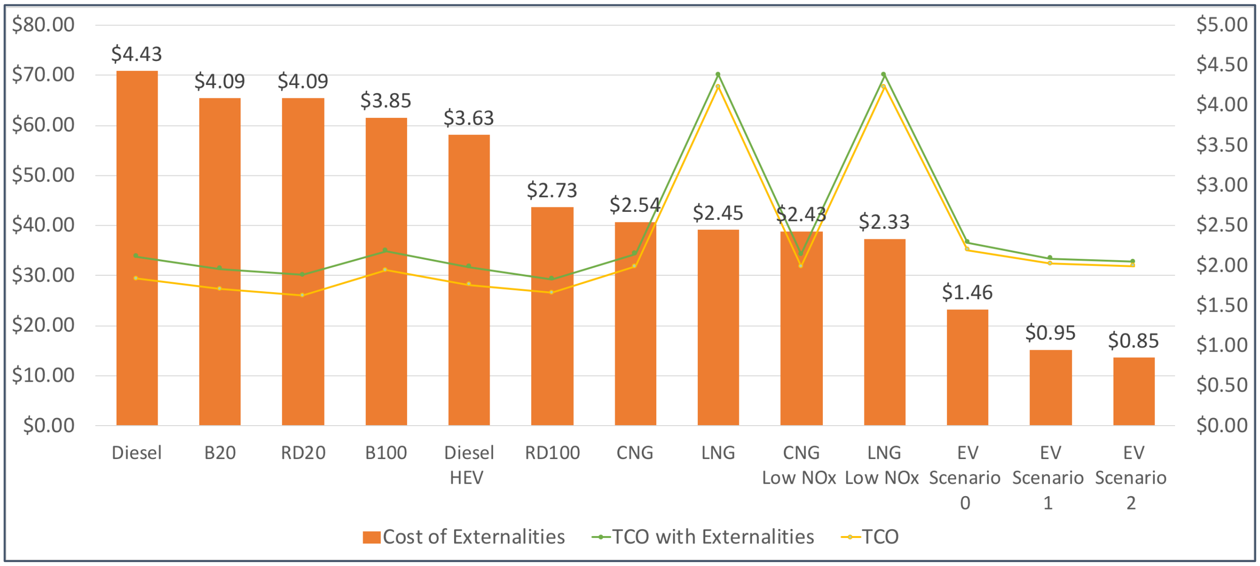


Figure 6 TCO and externalities for fleet provider 16

When comparing the total cost of ownership with externalities the results are not as favorable for the cleanest technologies due to the high capital investments required. **Error! Reference source not found.** shows the results of the TCO and externalities of all available technologies for fleet operator 3. Overall, biofuels and renewable diesel show a slightly better TCO considering or not externalities.

Figure 5 *TCO and externalities for fleet provider 3*



shows the results of the TCO and externalities of all available technologies for fleet operator 16. Biofuels, renewable diesel, and HEV technologies show a slightly better total cost of ownership than diesel considering or not externalities. BEV scenario 1 and 2 including externalities are below the diesel in this context.

Considering the benefits of BEV drivetrains and the associated available incentives, the additional scenarios explored the role of these monetary incentives in electricity prices and truck purchase price. To better assess the impact of each incentive scenario, two metrics were computed, the return on investment (ROI) of each dollar of incentive spent and its corresponding dollars of externalities reduced. The same figure can also be interpreted as the cost of abatement or the cost to reduce one dollar of externalities ($/pollutant abatement).

For the case of the first fleet company (Figure 7), the use of the HVIP voucher makes the BEV trucks (with externalities) competitive without any additional improvement of the energy efficiency, while the LCFS credit is not enough to bring the TCO lower than the diesel counterparts. Efficiency improvements (EER) are not enough to bring EV trucks to a competitive level with conventional diesel technologies, showing the important role of the purchase incentives. The cost of abatement with incentives for both scenario 1 and 2 are very similar and the efficiency improvement in scenario 2 reduces the overall TCO with externalities considered in this study by 1.6%. It is only with both incentive policies and efficiency gains that the BEV fleet's TCO can compete with a diesel fleet when considering the externalities, which aggregate both local and global pollutants Scenario 2 with HVIP is almost at the break-even point with diesel and it shows that the additional reduction in TCO from the use of LCFS might not be critical. The truck composition of fleet operator 3 requires the use of all efficiency improvements and both incentive programs to compete with diesel fleets accounting for externalities. Recalling Table 4, the data for this operator indicates that the annual VMT for the vehicles is low.

Error! Reference source not found. shows the results for PID 16, which has a fleet of only class 4 and 6 trucks. For scenario 0, the use of LCFS and HVIP incentives (separately or combined) bring EV trucks down to the same cost of diesel trucks considering externalities. Under scenarios 1 and 2, the improvement in efficiency (EER) is enough to bring EV at the same cost range with externalities of diesel. Fleet operator 16 shows a better benefit of improvements in energy efficiency for scenarios 1 and 2 for BEV trucks that are able to bring down their cost to compete with diesel ones, if considering externalities.

Overall, incentives are still required to support the transition to zero-emissions technologies, although for some operations (e.g., PID 16) the improvement in efficiency is enough to make both technologies competitive. However, each fleet has specific characteristics of truck classes and VMT, which affect the TCO of the entire fleet. But, with the HVIP incentive and the efficiency improvement of scenario 1, it is possible to achieve a competitive TCO at a lower cost of abatement (from 1.90 to 1.58). With no efficiency improvements, both incentive policies make it possible to reduce the TCO of the EV fleet below diesel with externalities, but when accounting for efficiency improvements seems that there is not much reduction in externalities in scenario 2, making the LCFS incentive not as efficient for this case.

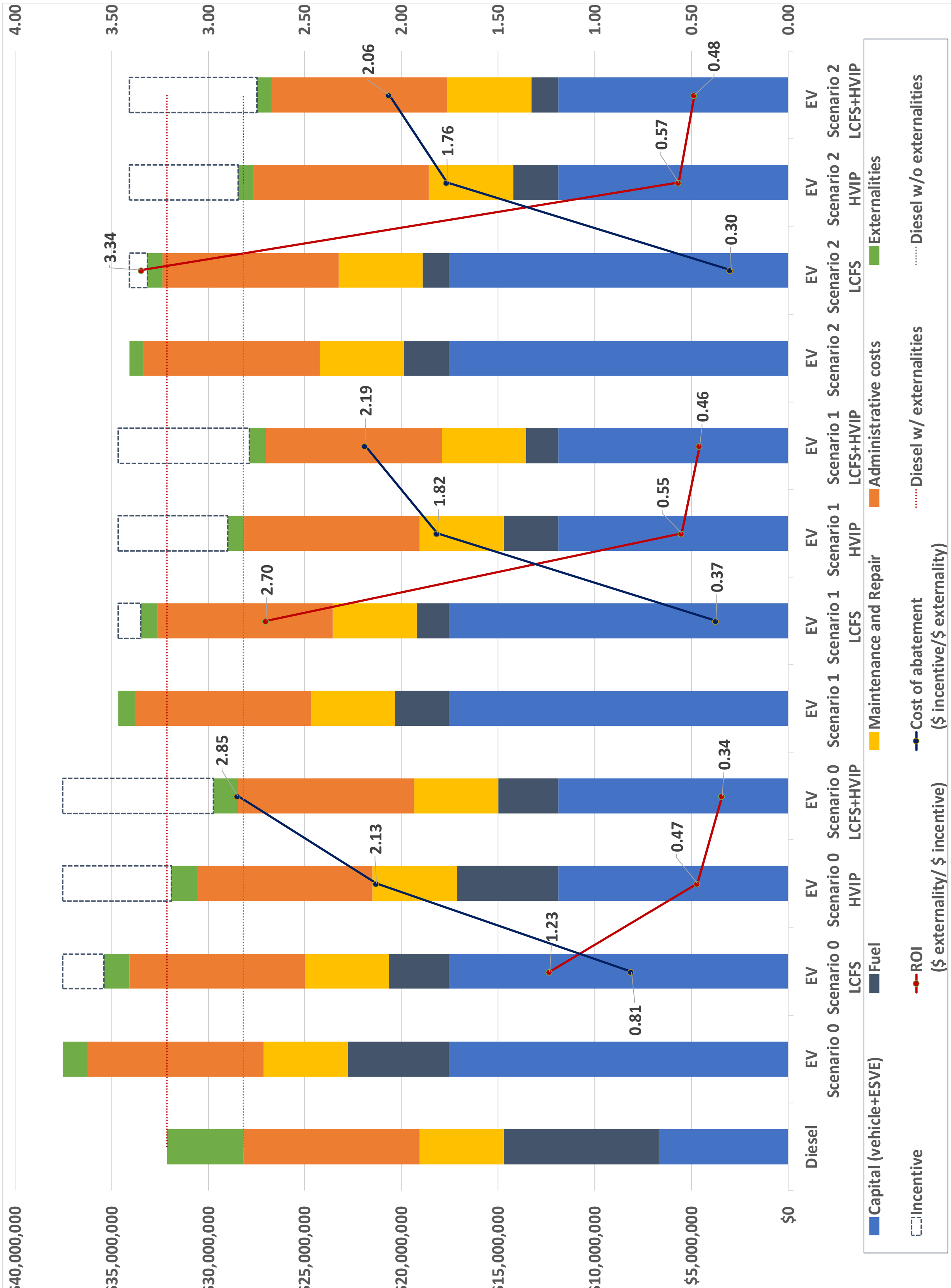


Figure 7 TCO results for PID 3 (EV scenario)

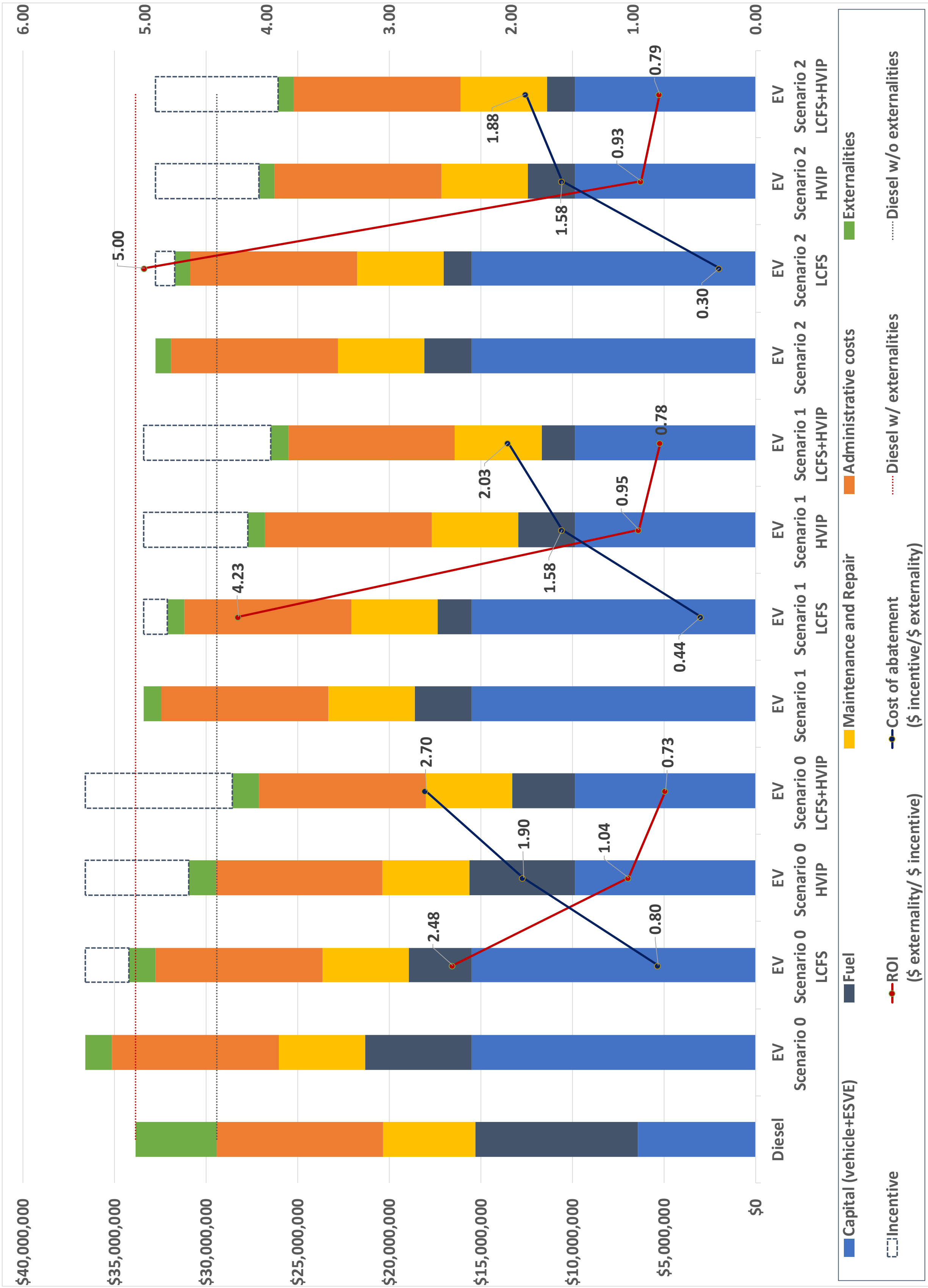


Figure 8 TCO results for PID 16 (EV scenario)

Table 8 shows the payback periods for each truck class for providers 3, 16 and using AFLEET 2017 default values of vehicle efficiency and VMT. Conversations with fleet managers, indicate that in general, companies look for payback periods of 3-5 years (with some parcel companies using the vehicles for a larger period). Under AFLEET default values, the increased efficiency and the use of financial incentives as in the case of scenario 2, make these vehicles achieve these low payback times. AFLEET 2017 VMT values, on average, are higher than those found in the two parcel fleet operators driving data and from the payback period results, mileage is an important parameter affecting the TCO of the trucks.

To better understand the impact of the HVIP incentive, a sensitivity analysis for a class 5 truck (commonly used for parcel deliveries operations) using provider 3 VMT values was conducted. Figure 9 shows different levels of HVIP incentive values and the associated payback period to that incentive. The current HVIP voucher for a class 5 truck is $80,000 resulting in a 12 years payback (accounting for externalities) for this operator. A $10,000 increase to this incentive decreases the payback period almost by half to 6.7; and with $20,000 more, it reaches 4 years. Setting this incentive between $20,000 and $25,000 more would lead to a breakeven point compared to the diesel vehicle considering or not externalities.

Table 8 Payback period for EV trucks

Payback period in years*		EV Scenario 0	EV Scenario 0 LCFS	EV Scenario 0 HVIP	EV Scenario 0 LCFS+HVIP	EV Scenario 1	EV Scenario 1 LCFS	EV Scenario 1 HVIP	EV Scenario 1 LCFS+HVIP	EV Scenario 2	EV Scenario 2 LCFS	EV Scenario 2 HVIP	EV Scenario 2 LCFS+HVIP	Annual VMT
PID 3														
Class 3		19.2	13.1	19.2	13.1	10.5	9.3	10.5	9.3	9.7	8.8	9.7	8.8	18,096
		26.0	15.9	26.0	15.9	15.2	12.7	15.2	12.7	14.0	12.2	14.0	12.2	
Class 4		46.5	28.1	19.3	11.7	21.6	18.5	8.9	7.7	19.5	17.4	8.1	7.2	12,380
		64.0	33.6	26.6	14.0	31.7	25.6	13.1	10.6	28.8	24.4	12.0	10.1	
Class 5		53.1	30.6	11.9	6.8	23.2	19.8	5.2	4.4	20.9	18.5	4.7	4.1	13,098
		69.7	35.6	15.6	7.9	33.4	26.8	7.5	6.0	30.3	25.6	6.8	5.7	
Class 7		168.6	85.9	94.8	48.3	62.4	52.4	35.1	29.5	55.6	48.7	31.2	27.4	8,809
		299.2	110.4	168.2	62.1	102.0	77.7	57.3	43.7	90.3	73.4	50.7	41.3	
PID 16														
Class 4		32.1	20.9	13.3	8.7	16.5	14.4	6.9	6.0	15.1	13.6	6.3	5.6	17,898
		44.9	25.7	18.6	10.7	24.4	20.0	10.1	8.3	22.3	19.2	9.3	8.0	
Class 6		73.1	39.0	24.6	13.1	28.7	24.3	9.7	8.2	25.7	22.6	8.6	7.6	11,044
		94.0	44.3	31.6	14.9	41.4	32.7	13.9	11.0	37.3	31.1	12.5	10.5	
AFLEET														
Class 3		13.6	8.9	13.6	9.0	7.1	6.2	7.1	6.2	6.5	5.8	6.5	5.8	21,750
		17.2	10.4	17.2	10.4	9.9	8.2	9.9	8.2	9.1	7.9	9.1	7.9	
Class 4		25.1	14.8	10.4	6.2	11.3	9.7	4.7	4.0	10.2	9.0	4.2	3.8	16,500
		30.4	16.5	12.6	6.9	15.6	12.7	6.5	5.3	14.2	12.1	5.9	5.0	
Class 5		25.1	14.5	5.6	3.2	11.0	9.4	2.4	2.1	9.9	8.7	2.2	2.0	19,750
		29.5	15.9	6.6	3.5	15.0	12.1	3.3	2.7	13.6	11.6	3.0	2.6	
Class 6		24.7	14.0	8.3	4.7	10.5	9.0	3.5	3.0	9.5	8.4	3.2	2.8	23,000
		28.8	15.3	9.7	5.1	14.4	11.6	4.8	3.9	13.1	11.1	4.4	3.7	
Class 7		14.6	8.8	8.2	4.9	6.7	5.8	3.8	3.3	6.1	5.4	3.4	3.0	65,000
		20.1	10.5	11.3	5.9	9.9	8.0	5.6	4.5	9.0	7.6	5.1	4.3	

*Note: For each truck class payback with externalities is shown in the first row, and for payback without externalities in the second row

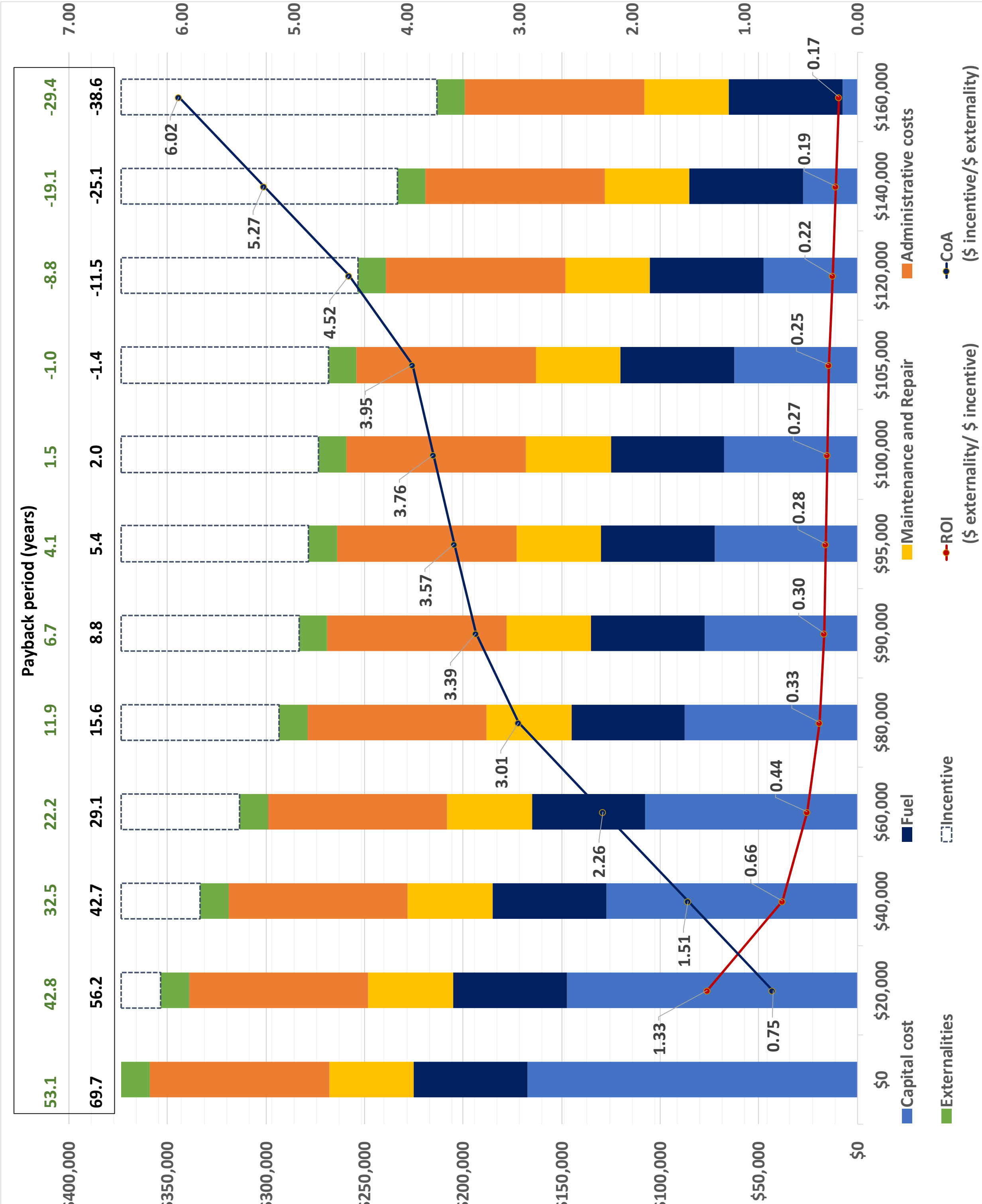


Figure 9 Different incentive impact for class 5 truck PID 3

*Note: Payback periods in green include externalities, those in black are simple paybacks without externalities

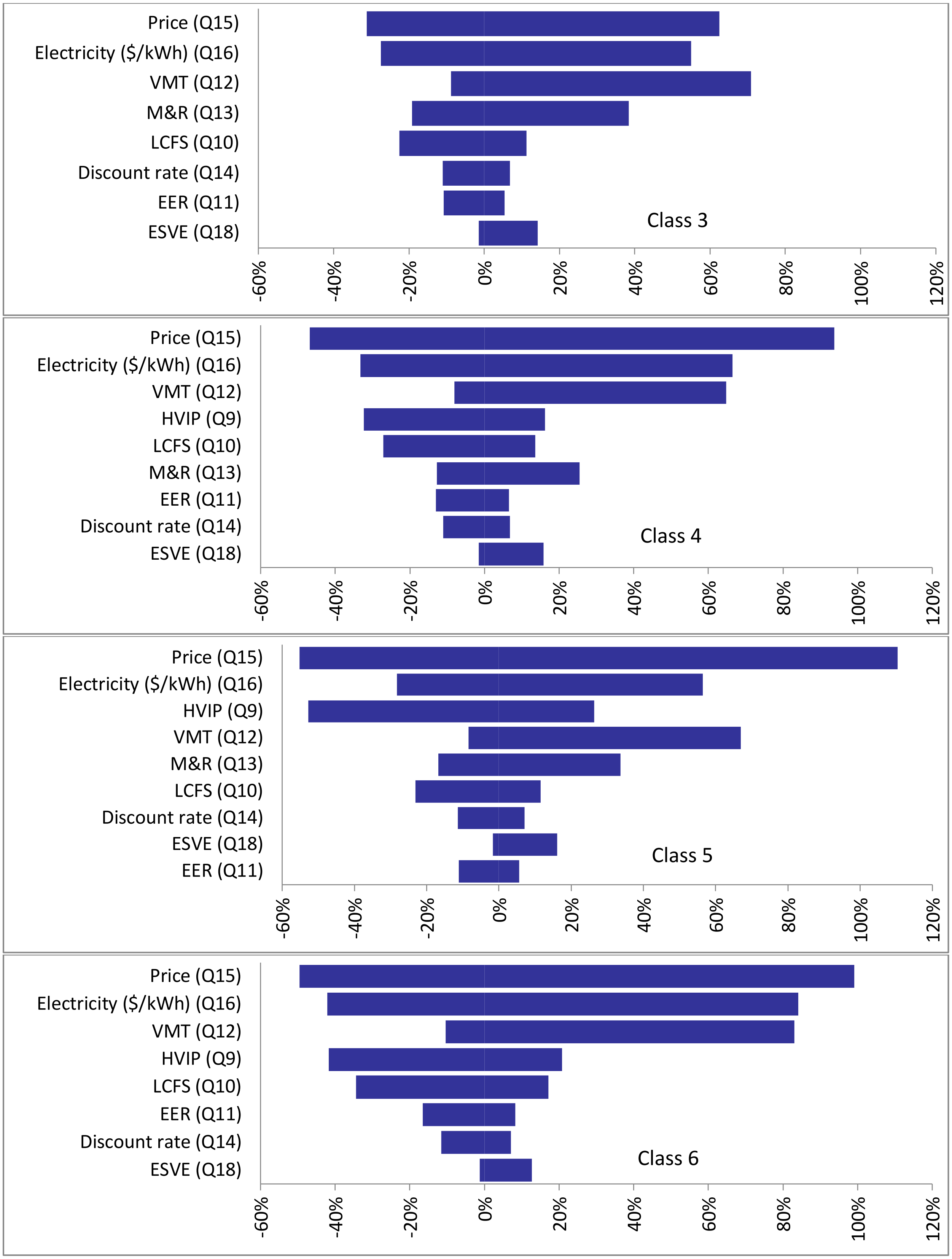
4.4. Sensitivity analysis

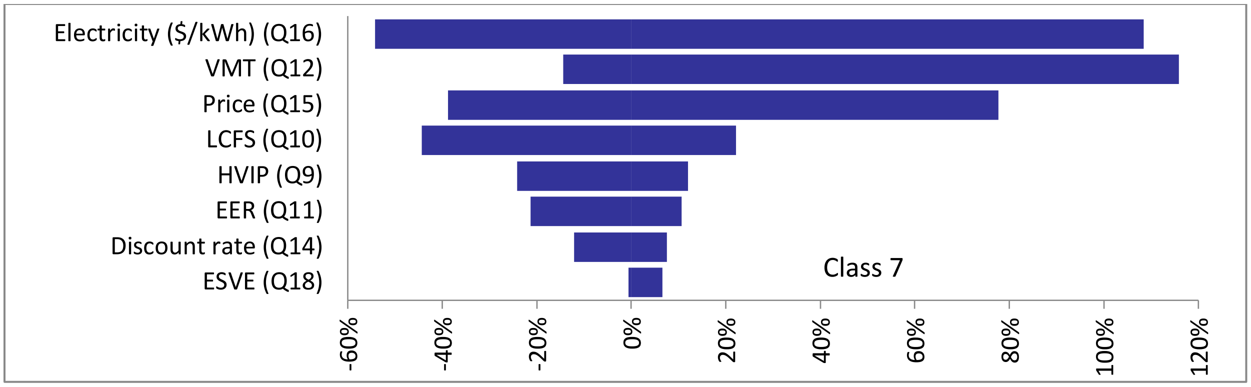
Finally, a sensitivity analysis was conducted to determine which parameters have a higher impact on the TCO of electric trucks. These parameters are: maintenance and repair, discount rate, EER/fuel economy, price, VMT, HVIP incentive, LCFS credit, electricity price and EVSE. All parameters, except EVSE were tested under a change of -100% to 200% from their baseline cost values (i.e., those in AFLEET 2017 except for updated fuel costs). The analyses examined EVSE costs at a range of -100% to 1000% change from AFLEET default costs to account for the additional costs associated with installation and grid upgrades discussed in previous sections. **Error! Not a valid bookmark self-reference.** Figure 10 shows the tornado graphs with the sensitivity analysis where parameters are varied (one by one) within the ranges mentioned above, and the x-axis shows the corresponding variation in the TCO of each class of truck.

Purchase price, electricity cost and VMT are the top parameters affecting the total cost of ownership of these vehicles. Purchase price and fuel cost are consequently affected by the incentives granted and can be seen in the tornado graphs that appear relevant for the truck TCO.

Consistent with previous results, purchase incentives are critical for making these technologies competitive against conventional diesel. Another important factor besides the cost of the technology are the use of these trucks; empirical results showed a much lower annual VMT than the values in AFLEET 2017. This difference has a major impact on the TCO and payback periods. Another interesting outcome is the effect of charging infrastructure which is not only the charger but the associated "make-ready" costs according to the fleet operation and requirements. If charging infrastructure costs were 10 times higher, the TCO impact would represent less than 20% of all the costs.

Figure 10 Sensitivity analysis for electric trucks. Percent change in TCO for classes 3-7


Price (Q15)
Electricity ($/kWh) (Q16)
VMT (Q12)
M&R (Q13)
LCFS (Q10)
Discount rate (Q14)
EER (Q11)
ESVE (Q18)
Class 3
-60%
-40%
-20%
0%
20%
40%
60%
80%
100%
120%
Price (Q15)
Electricity ($/kWh) (Q16)
VMT (Q12)
HVIP (Q9)
LCFS (Q10)
M&R (Q13)
EER (Q11)
Discount rate (Q14)
ESVE (Q18)
Class 4
Price (Q15)
Electricity ($/kWh) (Q16)
HVIP (Q9)
VMT (Q12)
M&R (Q13)
LCFS (Q10)
Discount rate (Q14)
ESVE (Q18)
EER (Q11)
Class 5
Price (Q15)
Electricity ($/kWh) (Q16)
VMT (Q12)
HVIP (Q9)
LCFS (Q10)
EER (Q11)
Discount rate (Q14)
ESVE (Q18)
Class 6



Note: All parameters vary from -100% to 200%, except for EVSE that goes from -100% to 1,000% from AFLEET 2017 cost baseline

5. CONCLUSIONS

Empirical data from different last mile delivery fleets shows operational differences among vocations, in particular, beverage, linen, food, and parcel delivery routes within a 100-mile distance represent more than 80% of their daily trips. More so, more than 95% of parcel routes are below this level. These are important findings because they show the opportunities for electrification in last mile distribution since these range requirements are easily fulfilled by commercially available technologies. Other available technologies considered to assess the performance and TCO of fleets like HEV, low carbon diesel fuels and natural gas can compete technically with conventional diesel trucks, but electric trucks pose themselves not only as a technically feasible alternative but the lowest petroleum use, GHGs and air pollutants (considering California grid) with noise reduction benefits and lower maintenance costs. Still purchase cost, payback period, uncertain infrastructure costs are key factors for fleet operators to transition to cleaner vehicles.

Thus, fleet driving data shows that trucks are traveling less miles than expected and this has an important impact in the payback periods.

Parcel deliveries are a growing component of urban freight distribution, especially due to the increase of the on-demand economy.

The results show different technology scenarios for BEVs with a combination of improved efficiency factors and monetary incentives, the latter remain vital to bring BEVs at a competitive level with diesel drivetrains. The analyses show the results accounting or not for externalities, this differentiation needs to be made since fleet managers are worried about the out of pocket expenses while government regulations bring the attention to externalities and a system-wide scope.

Individual analyses for different truck classes were developed to better understand the TCO and contribution of different truck classes to a fleet. Sensitivity analysis shows that VMT, purchase price and electricity cost are the main factors in the lifetime cost of a truck. As mentioned before, fleets were found to be driven fewer miles than expected (i.e. compared to AFLEET 2017 parameters) which greatly affects the payback periods. The other relevant factors related to vehicle price and electricity are directly affected by the HVIP purchase voucher and the LCFS credit. Smaller companies with constrained financial models make them more susceptible to external factors like vehicle purchase price or fuel prices. For the freight trucking sector to transition to cleaner vehicles it is required that alternative truck technologies have a higher market penetration and give certainty to companies that necessary incentives like HVIP and LCFS will remain for several years.

Therefore, last mile and especially, parcel fleets require these incentives to adopt zero-emission vehicles. But a more thorough study should be developed to improve the efficiency of the incentives available. The cost of abatement combining both incentives could show marginal benefits compared to diesel trucks. Likewise, pilot programs and real driving data will inform better about the needs of commercial fleets and vehicles operating in the U.S.

The most viable zero-emission technology is battery-electric trucks. Given current public policies and incentives in California for vehicles and electricity generation, electric mobility has become a clear pathway for the transportation sector and this includes last mile delivery distribution.

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