Journal

ITS Reports, 2017(33)

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Publication Date

2018-08-01

DOI

10.7922/G2JM27TW

UNIVERSITY OF CALIFORNIA

Evaluating the Use of Zero-Emission Vehicles in Last Mile Deliveries

A Research Report from the University of California Institute of Transportation Studies

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August 2018

PROJECT ID: UC-ITS-2017-33 | DOI:10.7922/G2JM27TW

ITS UCDAVIS INSTITUTE OF TRANSPORTATION STUDIES

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
UC-ITS-2017-33		

4. Title and Subtitle Evaluating the Use of Zero-Emission Vehicles in Last Mile Deliveries	**5. Report Date** August 2018 **6. Performing Organization Code** ITS-Davis
7. Author(s) Miguel Jaller Ph.D., https://orcid.org/0000-0003-4053-750X Leticia Pineda, and Hanjiro Ambrose https://orcid.org/0000-0002-6502-5191	**8. Performing Organization Report No.**
9. Performing Organization Name and Address Institute of Transportation Studies, UC Davis 1605 Tilia Street, Davis, CA 95616	**10. Work Unit No.** **11. Contract or Grant No.** UC-ITS-2017-33
12. Sponsoring Agency Name and Address The University of California Institute of Transportation Studies www.ucits.org	**13. Type of Report and Period Covered** Final Report (August 2016 – August 2018) **14. Sponsoring Agency Code** UC ITS

15. Supplementary Notes

DOI:10.7922/G2JM27TW

16. Abstract

While trucks may only represent a small share of the traffic in urban areas, they generate more than half of overall emissions for specific contaminants (Jaller et al., 2016). One of the approaches to contend with such issues is to promote the use of new technologies and alternative fuel pathways. This work conducts an empirical assessment of the economic and driving patterns of trucks used for last mile delivery given the increase in these vehicles serving even more densely populated areas (compared to the long-haul transport). The work concentrates on parcel deliveries, as they are typically used to transport the goods resulting from the rapidly growing e-commerce demand. The authors evaluate the performance by analyzing real driving data from parcel fleets (Walkowicz et al., 2014; Jaller et al., 2017a), and use the data to conduct life-cycle assessments (LCA) to estimate the various impacts. The contributions of the work are: 1) comparison analyses between parcel delivery driving data with other delivery vocations to identify different freight patterns. The analyses show the differences and similarities between the driving patterns when using different drivetrains for a number of parcel delivery vocations. 2) Estimation of delivery tour length distributions (TLDs), and specific fuel consumption (SFC) for different drivetrains and vehicle classes. And, 3) estimate the total cost of ownership (TCO), including externalities, of different truck technologies under numerous scenarios that assume changes in fuel efficiency and incentives of certain drivetrains. Additional sensitivity analyses are conducted to identify the key parameters that affect the TCO. Among these, the analyses show the efficiency of purchase and use incentives for these technologies. The results can be extrapolated to a system-wide scope for similar vocations with common operational variables and explore the benefits and costs of transitioning to zero-emission technologies.

17. Key Words	18. Distribution Statement
Zero emission vehicles, urban goods movement, trucks, alternate fuels, delivery service	No restrictions.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	77	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

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ACKNOWLEDGEMENTS

This study was made possible through funding received by the University of California Institute of Transportation Studies from the State of California's Public Transportation Account. The authors would like to thank the State of California for its support of university-based research, and especially for the funding received for this project.

DISCLAIMER

Evaluating the Use of Zero-Emission Vehicles in Last Mile Deliveries

UNIVERSITY OF CALIFORNIA INSTITUTE OF TRANSPORTATION STUDIES

July 2018

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Introduction

In 2015, the freight transportation sector moved USD$19.1 trillion (2012 USD) worth of goods (U.S. Department of Transportation and Statistics, 2016), with the road transport representing the largest share in both weight and tonnage. Over-the-road transport dominates because it is required for almost every movement along the supply chains and multi-modal systems. Long- and short-haul transport are the two main types of truck movements. While most of the research concentrates in the long haul, the truth is that the majority of the cargo have an urban area as the destination. Consequently, the cargo transported over the long haul also generates short haul movements. For instance, 85% of the truck traffic in Southern California are internal trips and deliveries in the region (SCAG, 2016).

Moreover, recent changes in supply chain management and operations, and rising home deliveries have exacerbated the challenges in the logistics of last mile distribution. Some of the key factors affecting these challenges are the advent of the on-demand economy, and the resulting growth in online shopping practices (UPS, 2016).

However, there is high complexity in understanding the true impacts of these trends because the on-demand economy not only affects logistics and freight movements but passenger travel and consumer behavior as well. Specifically, it is not conclusive that the relationship of online shopping and traditional shopping behavior, i.e. if there is a complementary, substitution and/or induced demand effect and how it translates into travel choices, and the associated vehicular traffic.

Although these trends and others will continue to affect the freight system, truck traffic today is generating congestion and is responsible for a disproportionate share of transport externalities. For example, while trucks may only represent a small share of the traffic in urban areas, they generate more than half of overall emissions for specific contaminants (Jaller et al., 2016). One of the approaches to contend with such issues is to promote the use of new technologies and alternative fuel pathways. The California Sustainable Freight Action Plan (California Governor's Office, 2016), for example, identified this measure as a priority, and set the following goals to address the various impacts: 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).

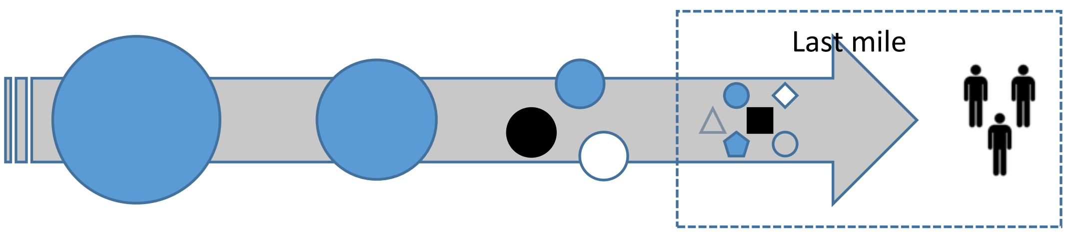
There are some economic, financial, technological, operational, and behavioral challenges to achieve these goals. For instance, fostering the use of zero and near-zero emission vehicles must address the fact that the companies and supply chains in the system have different fleet ownership, operations, and finance models. Consequently, there are a wide range of factors that would affect achieving the efficiency gains, and the penetration of zero or near-zero emission vehicles in their fleets. Moreover, vehicles have different uses throughout their lifetimes, and the drivetrain configurations may only fit a specific vocation. Considering the growing importance of the last mile and how the vehicles are serving even more densely populated areas (compared to the long-haul transport), this work conducts an empirical assessment of the economic and driving patterns of trucks in these delivery vocations. The work concentrates on parcel deliveries, as they are typically used to transport the goods resulting from the rapidly growing e-commerce demand. The authors evaluate the performance by analyzing real driving data from parcel fleets (Walkowicz et al., 2014; Jaller et al., 2017a), and use the data to conduct life-cycle assessments (LCA) to estimate the various impacts. The contributions of the work are: 1) comparison analyses between parcel delivery driving data with other delivery vocations to identify different freight patterns. The analyses show the differences and similarities between the driving patterns when using different drivetrains for a number of parcel delivery vocations. 2) Estimation of delivery tour length distributions (TLDs), and specific fuel consumption (SFC) for different drivetrains and vehicle classes. And, 3) estimate the total cost of ownership (TCO), including externalities, of different truck technologies under numerous scenarios that assume changes in fuel efficiency and incentives of certain drivetrains. Additional sensitivity analyses are conducted to identify the key parameters that affect the TCO. Among these, the analyses show the efficiency of purchase and use incentives for these technologies.

The results can be extrapolated to a system-wide scope for similar vocations with common operational variables and explore the benefits and costs of transitioning to zero-emission technologies.

Supply Chains and Last Mile Operations

The term "last mile distribution" often describes the last leg of the supply chain where goods or products and services reach the final consumer or destination. Contrasting with the other stages or echelons in the chain, the distribution configuration in the last mile can be very different. This is because, in many cases, the destination is the ultimate consumer, and small batches or retailing occurs with more frequent trips and shorter distances. This generates inefficiencies trying to match multiple demands of products from different consumers in alternate locations, times and schedules. Empty trips and less than truck-load (LTL) also account for the main operational inefficiencies. Additionally, the last mile distribution usually happens within the urban context in which congestion has a big impact in logistics operations (Gevaers et al., 2011; Rodrigue, 2013). Figure 1 provides a general depiction of how the flow of goods start as homogeneous and large shipments, and as they advance closer to the final consumers they break into smaller batches and heterogeneous products or goods.

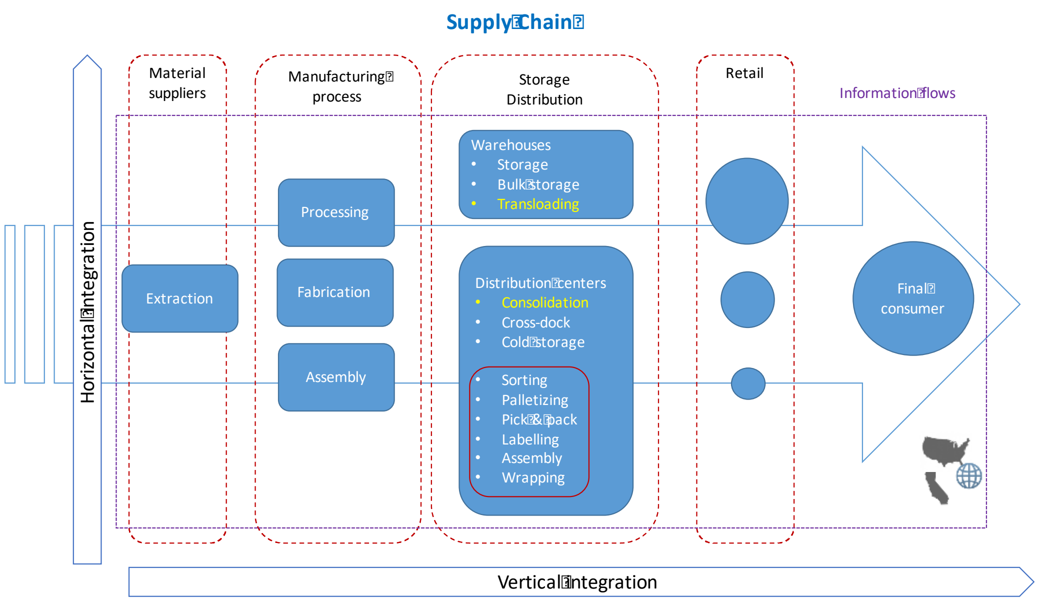
Figure 1. Goods distribution flow



Different stakeholders and their interactions facilitate this flow of goods such as shippers, carriers, receivers, warehouses/distribution centers (W&DC), and end-users, among other agents. Shippers produce and ship goods on their own or through carriers or third party logistics (3PL) which are logistics intermediaries for a leg or more of the supply chain (some large retailers can fall into this category). Carriers transport goods as for-hire to any company or as private companies serving a related company. W&DCs serve as storage facilities, but in the case of distribution centers, they perform other activities such as consolidation, pick and pack, and use a high level of automation and information technologies (Bowen Jr, 2008). Receivers are the destination agents, which usually set specific times and schedules to receive shipments. Receivers include the final consumer or an intermediate destination within a supply chain. The final consumer is the ultimate point in the supply chain. While there may be other intermediate consumers that add some value to the products received, the final consumers are expected to be the last destination, at the same time, they may generate returns of the products or reverse logistic flows.

All these agents interact as independent or integrated companies representing the production and consumption (PC) link, in which the various entities produce, process, transform, and store the goods until they reach their endpoint. Each supply chain is different and many PC links may occur with specific origins and destinations that are connected with freight trips (Holguín-Veras et al., 2012). Figure 2 shows a general supply chain, the dotted figures represent echelons along the chain. Each pair of echelons refers to the PC links mentioned before.

Figure 2. General supply chains



Source: Adapted from (Rodrigue, 2013)

Information and communication technologies (ICT) have augmented traditional supply chains allowing for better integration of systems and stakeholders within the same company, and across other suppliers. Consequently, there is an increase of information flows that help reduce uncertainty leading to shorter delivery times, smaller batch sizes, and optimal inventories (Fiala, 2005). In general, supply chains serve the most common commercial interactions: Business to business (B2B), Business to consumer (B2C) and Consumer to consumer (C2C) (Visser and Nemoto, 2003; Visser and Lanzendorf, 2004). B2B accounts for the highest value of transactions, but B2C is changing the configurations of urban and residential deliveries in terms of frequency and delivery time which will impact congestion and land use patterns (Mokhtarian, 2004).

Last Mile Distribution

Products can reach the final consumer in two ways, one through retail stores where customers purchase goods from, and second, where goods are delivered directly to the consumer (Rodrigue, 2013). These two systems have different structures, and especially the latter has been highly affected by the on-demand economy and online shopping.

Inbound flow of goods at retail stores have more consolidation and larger volumes than those going directly to the consumer. The distribution to these stores typically allows for the use of larger vehicles, full-truck loads, and has fewer stops in their tours (Table 1). Even packaging and space utilization inside trailers or containers play a role to maximize the capacity of the freight systems.

Retail stores tend to locate in denser areas where customers benefit from higher accessibility. On the other hand, warehouses and distribution centers (W&DC) typically establish in the outskirts where there is more availability of land and rents are more affordable Figure 3. Nonetheless, a recent study also shows that in some locations this sprawling trend has ceased in the last years, specially e-fulfillment centers for expedite deliveries are moving closer to the markets they serve (Jaller et al., 2017b).

Table 1. Comparison between traditional retailing and online commerce

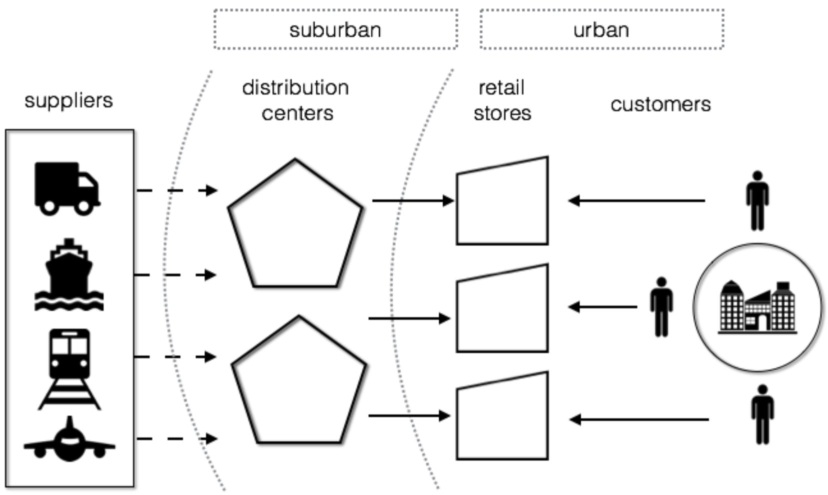
	Traditional retailing		**Online retailing**
	Retail stores (inbound) delivery	**In-store consumer purchase**	
Purchase frequency	Low/Medium	Low/High	High
Volume or quantity of products	Large quantities	Medium/Small quantities	Smaller quantities
Goods flows	Product and goods are delivered to retail stores and customers buy them there		deliveries to the customer at their home, work or alternative points
Supply chain	Push demand	Push demand	Pull demand
Information and communication technologies (ICT)	B2B information to fulfill inventories (ERP)		B2C information and tracking of orders -> B2B
Delivery trucks/vehicles types	Larger trucks or trailers	Passenger vehicles	Medium and smaller trucks or vans, bicycles or walk
Maximization of space (FTL/LTL)	Full Truck Load (FTL) (homogeneous loads)	N/A (heterogeneous loads)	Less than truck load (LTL) (heterogeneous loads)
Location of delivery points	Urban and suburban	Urban and suburban	Residential, urban and highly dense areas
No. delivery points in a tour	Few/One stops	Few/One stops	Many stops
Delivery failures	N/A	N/A	Many/Few

Source: Adapted from (Visser and Lanzendorf, 2004)

Although home distribution schemes existed long before with catalog or mail deliveries, it did not have today's advanced use of information and communication technologies and services. Companies adapting to e-fulfillment supply chains undergo changes in their distribution patterns, real estate footprint, logistics facilities, and vertical integration (Rodrigue, 2013). Moreover, the progress of enterprise resource planning (ERP), material requirements planning (MRP), radio frequency identification (RFID), GPS, mobile systems and other information technologies have enhanced supply chain management (Tseng et al., 2011). Due to the high level of integration required and the level of throughput, companies are achieving economies of scale by a vertical integration in the supply chain controlling a higher number of activities that aim for a seamless process (Rodrigue, 2013).

In the case of products directly distributed to customers, more agents participate in the final delivery. Customers can place an order through e-retailers or marketplaces, and the same company or third-party facilities start processing those online orders, in many cases 24/7. Goods follow a path through different facilities in the supply chain until reaching the final customer (Figure 4). These facilities include: e-fulfillment centers, parcel sorting centers or hubs, local parcel delivery centers or urban logistic depots, processing centers for returns and alternative pick up points (Rodrigue, 2013; Morganti et al., 2014). ICTs enable tracking of products throughout the supply chain and provide real time information among the agents about the commercial, financial and logistic operations.

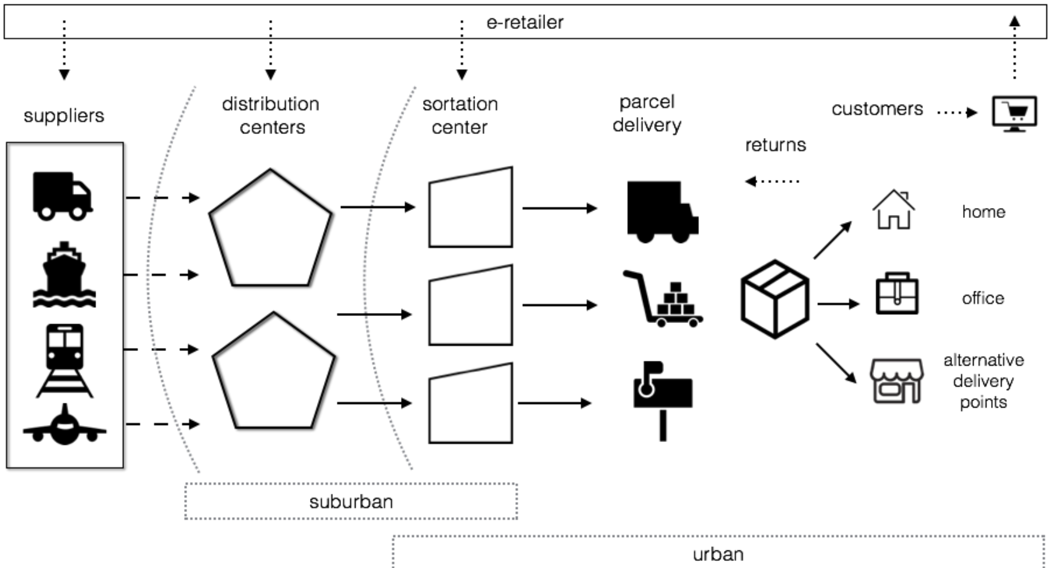
Figure 3. Traditional retail distribution



Two key aspects to consider in on-demand supply chains, are delivery fees and the structure of reverse logistics. This is important because free and hassle-free returns are among the factors the customer value when making purchasing decisions. The rate of return varies among types of products, with clothing resulting in high return rates, for example (UPS, 2016b. Expedite delivery times are becoming the standard and the implementation of subscriptions with a flat-rate are pushing more to lower delivery costs (Morganti et al., 2014).

Ironically, the efficiencies to offer rush deliveries may be creating system-wide inefficiencies. To be able to offer these –rush and expedite– services, companies are establishing smaller warehouses or e-fulfillment centers near the city centers to improve the level of service for their customers. This trend deserves further analysis to understand its impact.

Figure 4. E-retailing distribution



Impacts of E-Commerce

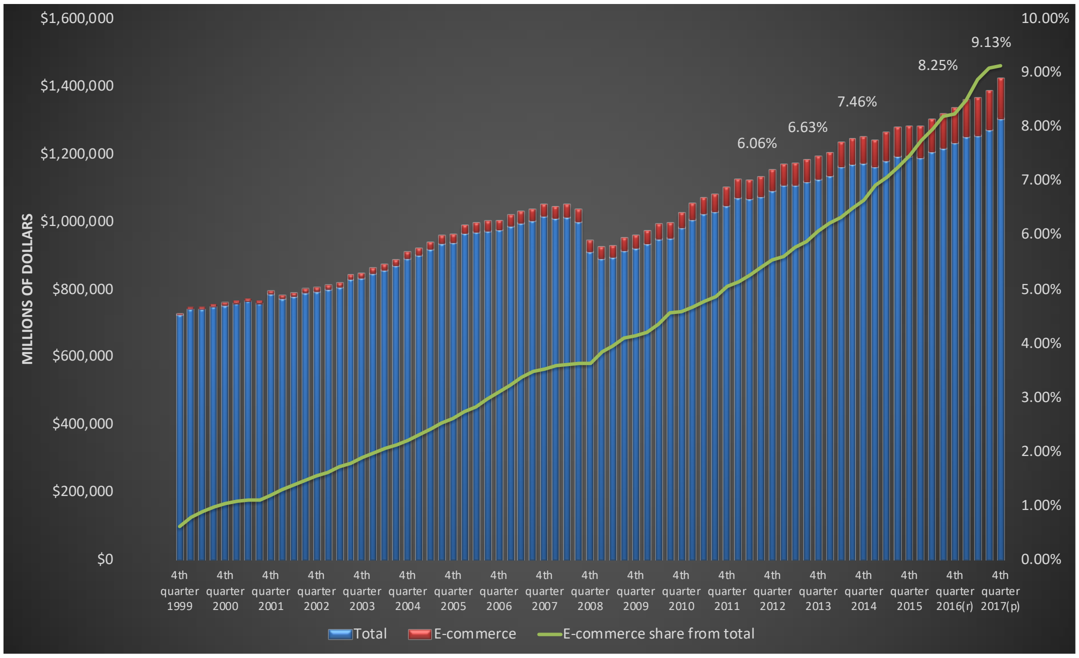
Online shopping has steadily grown in the last decade in the United States. According to the latest report on e-commerce retail sales in the U.S. (U.S. Census Bureau, 2017)[1], it accounts for $453.5 billion or 8.9% of total retail sales in 2017 (Figure 5). This shows an increase of 16% from 2016.

Online shopping growth rates are projected to maintain at a rising trend as it has been seen in both mature and developing markets, an example of this is India, with an impressive nearly 300% growth rate. It the U.S., the e-commerce market forecasts 25 billion parcels annually over the next ten years (Morganti et al., 2014; Joerss et al., 2016).

User penetration in the U.S. for 2017 is estimated at 78.3% with an average revenue per user of US$1,734.05. 83% of people in the U.S. use internet and 68% have a smartphone, these numbers confirm the high impact and penetration of ICT and the potential market for e-commerce (Statista, 2017).

[1] https://www.census.gov/retail/mrts/www/data/pdf/ec_current.pdf

Figure 5. Retail and e-commerce quarterly sales 1999-2017



Source: Own with data from U.S. Census Bureau (2017)

The impacts of online shopping fall on different spheres: consumer's activity and travel behavior, and freight and logistics. Impacts on consumer's activity and travel behavior relate to potential decisions changes in the short, medium and long term regarding the location of residence, lifestyle, car ownership, modification, and substitution or complementary effects of online and store shopping and travel, among others (Visser and Lanzendorf, 2004; Circella, 2017). The impact in freight and logistics systems include reductions in transaction costs through online channels, which leads to an increase in the purchasing power of consumers and thus, their demand. More and more e-retailers are increasing the level of service to attract more customers and compete with other companies. As previously explained, this is creating new configurations in the transportation and delivery systems that respond to higher frequencies, faster deliveries, adapting freight vehicles to enter residential areas, reverse logistics, induced freight traffic demand, location of distribution centers near customers, and consolidation and cooperation with other stakeholders (Visser and Lanzendorf, 2004).

Truck Technologies and Applications in Last Mile Deliveries

The last section provided a brief overview of the different supply chains, inefficiencies in last mile distribution and some of the impacts of online shopping. The opportunities to improve freight systems can be encompassed into two groups, one related to operations and the other regarding vehicle technologies. This chapter will elaborate more on the applications of zero-emission vehicles and how these technologies could improve last mile delivery operations.

Supply chains are constantly evolving and adapting to new requirements and constraints but also from innovations in information and communication technologies, resource planning, and interactions among agents. Improving logistic operations requires a comprehensive understanding of these interactions along the different stages in the supply chain. This requires a good amount of information and processing of data which in many cases is not achievable by all agents due to their scope, and limited resources or capacities. In the last few years, one of the most important drivers of change in supply chains is the on-demand economy and further research is required to unravel its impacts across sectors.

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. For example, Table 2 compares the efficiency between hybrid electric and electric trucks. 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, natural gas, electric and hydrogen fuel cell (IEA, 2017). All of these technologies offer different energy efficiencies, infrastructure and operational costs, green-house gases (GHGs) and criteria pollutant emissions which can be suitable for specific vocations and drive cycles. However, the comparison of these technologies requires total cost of ownership and lifecycle assessment analyses.

Today, most of the applications and pilots focus on electric technologies due to the readiness of the vehicle technology and associated infrastructure. The deployment of other policies incentivizing cleaner electric generation make electromobility a viable solution for passenger vehicles and trucks.

In particular, battery electric trucks have a limited driving range compared to other drivetrains but they are suitable for urban drive cycles characterized by low average speeds and high number stops. Technologies like regenerative breaking allow to recover energy from breaking that would otherwise be lost (Crolla and Cao, 2012). Similar to passenger electric vehicles, current electric trucks' operational limitations and price have hindered their general adoption in commercial fleets. Truck drivers also experience "range anxiety" derived from uncertainties about the true range of the vehicle and are constrained to specific routes and destinations where available charging, fueling, or reloading infrastructure must exist (Feng and Figliozzi, 2012; Davis and Figliozzi, 2013).

Researchers have investigated the application of zero-emission vehicles in different freight vocations using general modeling schemes and optimizations methodologies (Hackney and De Neufville, 2001; Ang-Olson and Schroeer, 2002; Lee et al., 2009; Zanni and Bristow, 2010; Demir et al., 2011; Den Boer et al., 2013; Lee et al., 2013; Bachmann et al., 2014; Demir et al., 2014; Quak and Nesterova, 2014).

Table 2. Pilot tests for delivery trucks

MPG (DGE)	Diesel	HEV	EV	Details	Source
Class 3	11.2		76.8	CAlHEAT- Navistar eStar In-Use Route	(CARB, 2018)
			46.1	Navistar eStar	(Giuliano et al., 2018)
Class 4	10.6	13		Thirty-Six Month Evaluation of UPS Diesel Hybrid-Electric Delivery Vans - 2012	(Lammert and Walkowicz, 2012b)
	10.2	13.1		UPS Hybrid Electric Delivery Vans - 2010	(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	(Lammert and Walkowicz, 2012a)
	7.9	9.4		UPS Hybrid Electric Delivery Vans - 2013	(Lammert and Walkowicz, 2012a)
	8.8	10		UPS Hybrid Electric Delivery Vans - 2014	(Lammert and Walkowicz, 2012a)
			24.9	Smith Newton Trucks	(Giuliano et al., 2018)
Class 7	10.7		30.6	FREVUE 2017	(Quak et al., 2017)

For examples, Ambrose and Jaller (2016) looked at the case of drayage trucks at the ports and assessed the impact of different fuel feedstocks and electricity generation portfolios. The analyses identified emissions and infrastructure cost differences at various points of the studied system from truck operations, including projected container volumes from 2015-2035 (CARB, 2006). The authors focused on use-phase greenhouse gases (GHG) and other criteria pollutants like nitrogen oxides (NOx) and particulate matter (PM) of electric and diesel trucks. The study concludes that the implementation of current electric technologies would be relevant only when operations expand to off-dock areas achieving emissions reductions of 30-40%. Current technologies do not allow for full implementation in this context, tough plug-in hybrid electric vehicles (PHEV) could be an alternative (Miyasato et al., 2015).

Other studies centered in last mile distribution show important opportunities for alternative vehicle technologies. Bachmann et al. (2014) analyzed urban delivery trucks operations in Canada by comparing diesel and hybrid-electric (HEV) drivetrains with a life-cycle assessment (LCA) model. They show CO_2 emission reductions of 25% by using HEVs. Similarly, Lee et al. (2013) performed a LCA of electric vehicles for urban deliveries estimating the energy and fuel use, emissions and total cost of ownership (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 and purchase price.

In Europe, as part of the Freight Electric Vehicles in Urban Europe (FREVUE) project (European Union, 2016), Quak et al. (2016a); Quak et al. (2016b) analyzed a number of case studies that include approximately 100 zero-emission vehicles of demonstration projects in participating cities like 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 its operational costs of fuel and maintenance offset the incremental costs (Duarte et al., 2016). In London, the demonstration project of a parcel company found that battery capacity was not depleted at the end of the runs leading to reductions in capital and operation costs.

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 (CARB, 2018). This can also be expanded to other classes and vocations, see Figure 6.

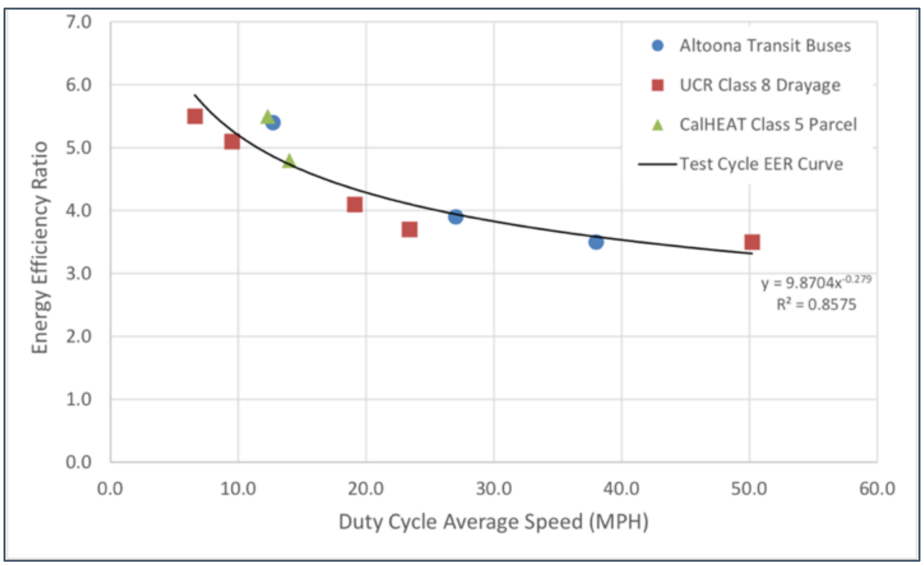
CalHEAT and CALSTART (2013) show the results of a pilot for parcel delivery vocations comparing electric trucks versus diesel using on-road and dynamometer testing. The outcome shows that electric trucks are 4 times more efficient and cheaper to operate than conventional diesel vehicles overall, although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

Another key aspect to consider for operating electric fleets is charging infrastructure (EVSE) installation and operation which relates to grid upgrades, landlord permits, charging time per vehicle, infrastructure and vehicle operation and maintenance (Quak et al., 2016a; Quak et al., 2016b). There are four common charging configurations discussed in the literature: 1) depot-charging; 2) public charging, 3) inductive charging, and 4) battery replacement. In the European tests, participating companies revealed that depot-charging was a suitable option for their fleets but one charger per vehicle is required, which may imply additional infrastructure investments. Charging operations are performed overnight as well as other operation activities such as maintenance. Charging time is determined by the characteristics and size of the battery, its use and charging infrastructure (Quak et al., 2016a; Quak et al., 2016b).

Still the higher cost of these alternative 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 directly to the cost of the truck for eligible technologies (CARB and CALTRANS, 2018). As of July 1, 2018, 3,344 vehicle purchases used the incentive program and around $110 million are still available. Most of the vouchers have been used to purchase hybrid vehicles (70%), followed by zero-emission vouchers, see Figure 7.

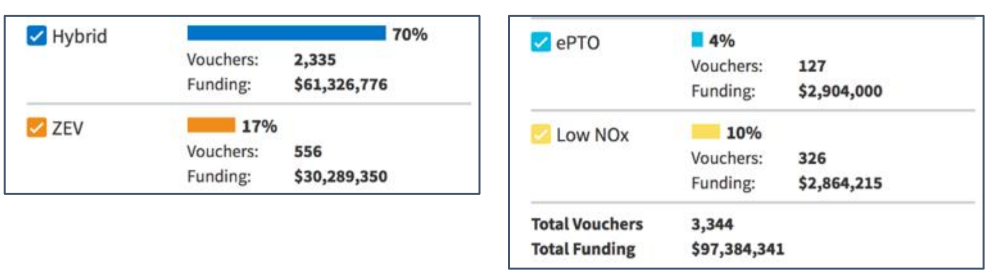
The eligible technologies of the HVIP program are: battery-electric, fuel cell, hybrid and ultra-low NOx natural gas engines. The voucher is different among technologies from approximately $2,500 to $100,000; battery-electric and fuel-cell trucks have the highest incentive amount. See Table 3 for some delivery truck examples.

Figure 6. Energy efficiency ratios and average speed of different truck vocations



Source: (CARB, 2018)

Figure 7. HVIP voucher implementation



Source: (CARB, 2018)

Table 3. Delivery truck HVIP incentive examples

			
Class	5	5	4
Type	Cab chassis	Step Van	Cargo Van
Max Speed	60 mph	67 mph	60 mph
Manufacturer	BYD motors	Workhorse	Zenith motors
Range	155 miles	150 miles Range plug 60 miles Extended range 60 miles	135 miles
Technology	100% Battery electric Iron-Phosphate Battery capacity: 145 kWh	100% battery electric Battery capacity: 60 kWh	100% Battery Electric Battery capacity: LIFePO 4 70 kWh
HVIP amount	$80,000	$80,000	$50,000

Source: (CARB and CALTRANS, 2018) Updated July 1, 2018

Characterizing Last Mile Delivery Operations

To model the impacts of zero emission vehicles in last mile operations in the U.S., the authors used real drive data to understand drive patterns among different vocations for commercial vehicles. This is important because companies in different industry sectors carry specific cargo and have particular freight trip production and attraction patterns (Jaller et al., 2015a; Jaller et al., 2015b). In this study, the authors assessed the operational performance and the environmental and energy impacts of different commercial delivery fleets using daily activity and freight tour characteristics.

Methodology and Data

The analyses use the public available information from the Fleet DNA project–Commercial Fleet Vehicle Operating Data–of the National Renewable Energy Laboratory (NREL) (Walkowicz et al., 2014; Walkowicz, 2014). Fleet DNA is a composite of driving data of medium- and heavy-duty commercial vehicles within weight classes 2 to 8. It includes relevant information about the operation of different truck technologies. 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. The final dataset had almost 700 days of information for 79 vehicles of conventional diesel, parallel and hydraulic drivetrains aggregated under two service providers or companies.

For the total cost of ownership analyses, the authors used the California Alternative Fuel Life-Cycle Environmental and Economic Transportation (AFLEET 2017) tool. AFLEET 2017 allows estimating energy use, GHGs, criteria pollutants and total cost of ownership for alternative fuel and vehicle technologies. It builds on the GREET 2016 model to generate well-to-wheels analyses, excluding vehicle manufacturing, and on the Environmental Protection Agency's Motor Vehicle Emission Simulator (MOVES) to estimate tailpipe emissions. The tool uses several data sources for its costs estimates (Argonne National Laboratory, 2016).

The methodology applied to analyze the data and characterize last mile delivery operations for parcel delivery comprises 4 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. Statistical analyses for parcel only delivery fleets to determine the relationships and significance of those patterns between the operators, considering vehicle characteristics and operations.

3. Delivery tour length distributions (TLDs) and specific fuel consumption (SFC). TLDs allow for a better comparison between vocations in terms of vehicle miles traveled and to identify the minimum range required by a vehicle to fulfill its trips or tour.
4. Finally, a comparison of the TCO of two fleets from FleetDNA, evaluated under several fuel technologies using AFLEET 2017. Development of sensitivity scenarios for electric trucks to show the main factors that affect the TCO and the effectiveness of financial incentives.

Last Mile Delivery Vocations

Table 4 shows summary statistics for all delivery vocations–beverage, warehouse, parcel, linen, food, local and parcel. Parcel has the shortest daily vehicle miles traveled (DVMT). Local delivery accounts for almost three times more DMVT than parcel, and other sectors like warehouse and food delivery also surpass parcel.

Table 4. Summary statistics for daily vehicle miles traveled 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

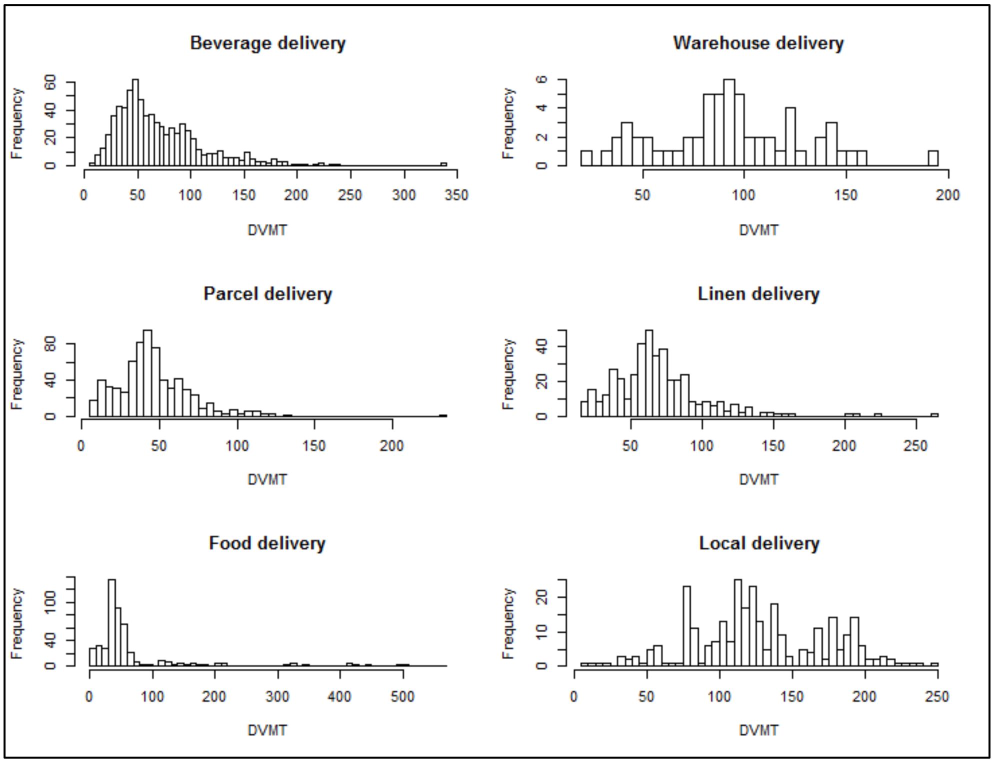
Source: Own with information from Fleet DNA (Walkowicz, 2014)

Figure 8 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 (see Part a). It is worth to notice that both local and warehouse vehicles are only conventional diesel which may explain their higher range. The 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. Moreover, within a 100-mile distance, beverage, linen, food, and parcel delivery routes represent more than 80% of all the delivery DVMT in the sample (with parcel having more than 95% of its routes below this level). These are important findings because they show the opportunities for the introduction of different vehicle technologies under current technological constraints (e.g., mile ranges between 100 and 120 miles), see part c.

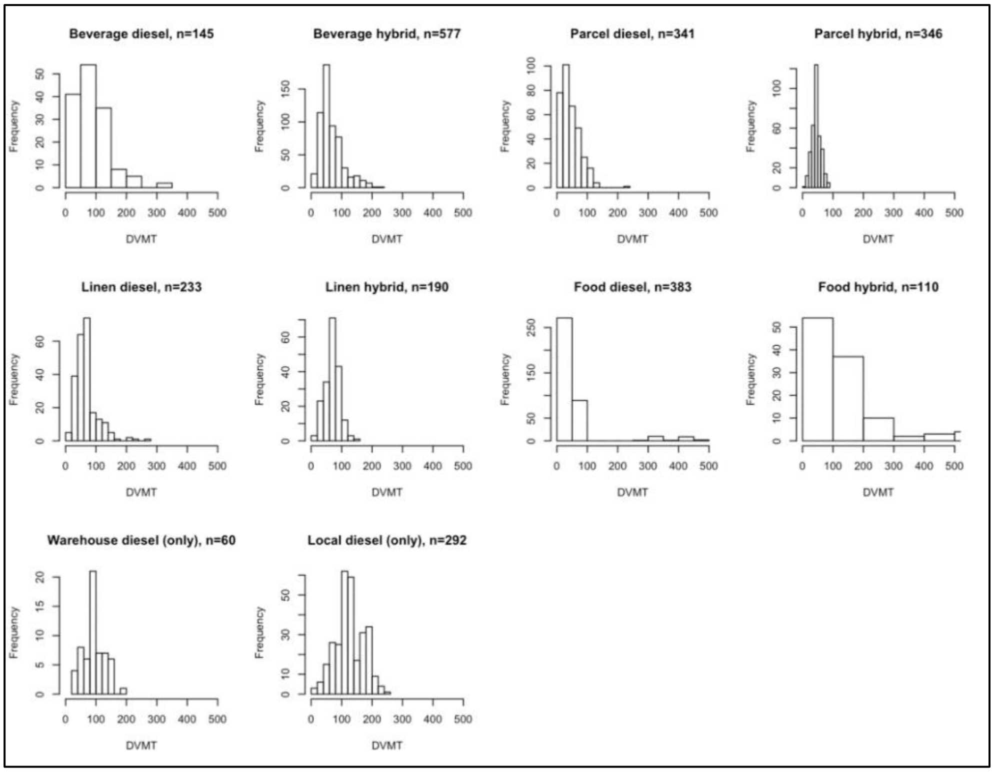
It is worth noticing that there are factors such as geographic location, type of urban area, particular origins and destinations that may have a great impact on these distances; however, the authors consider that the data offers important insights into these last mile delivery operations. Additionally, although a small sample, the values in Table 4 include different vehicle classes, and a number of undisclosed geographic locations, from different service providers. The following section concentrates on the parcel delivery vocation.

Figure 8. Daily vehicle miles traveled for last mile delivery vocations

a. All vehicles

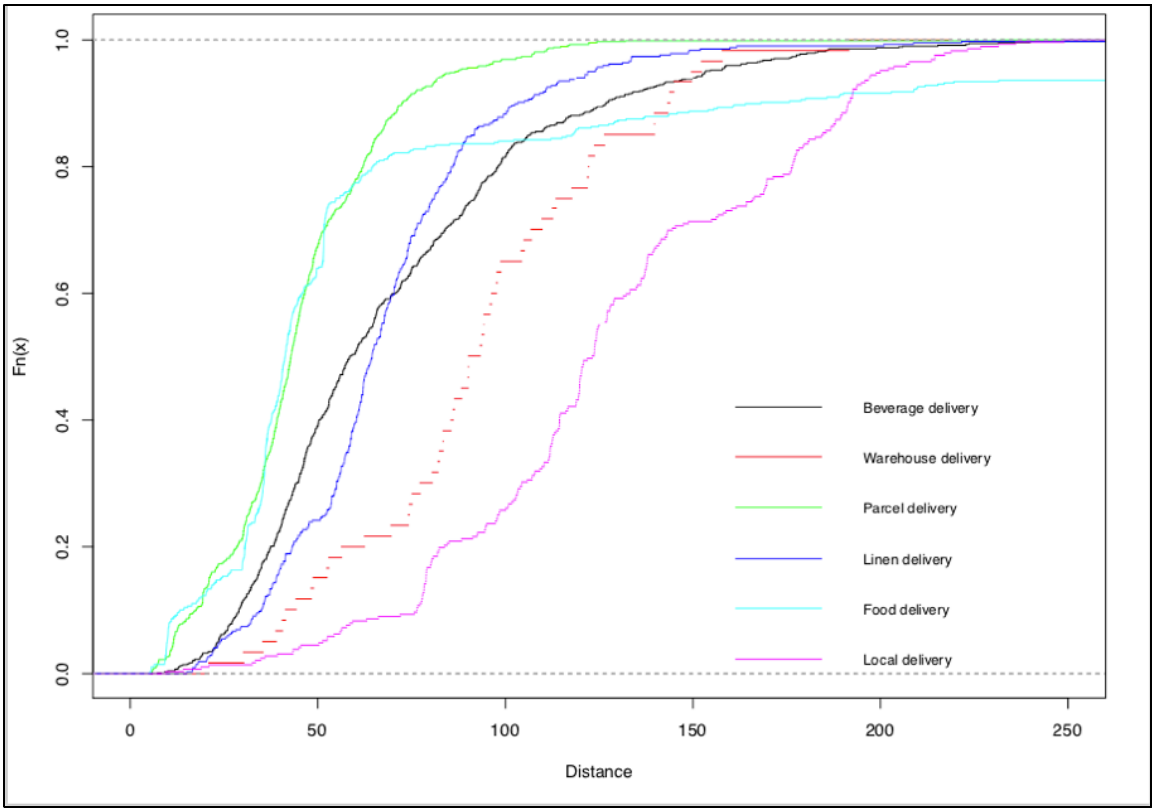


b. Conventional Diesel and Hybrids



Source: Own with information from Fleet DNA (Walkowicz, 2014)

Figure 9. Cumulative vehicle miles traveled distances per vocation



Source: Own with information from Fleet DNA (Walkowicz, 2014)

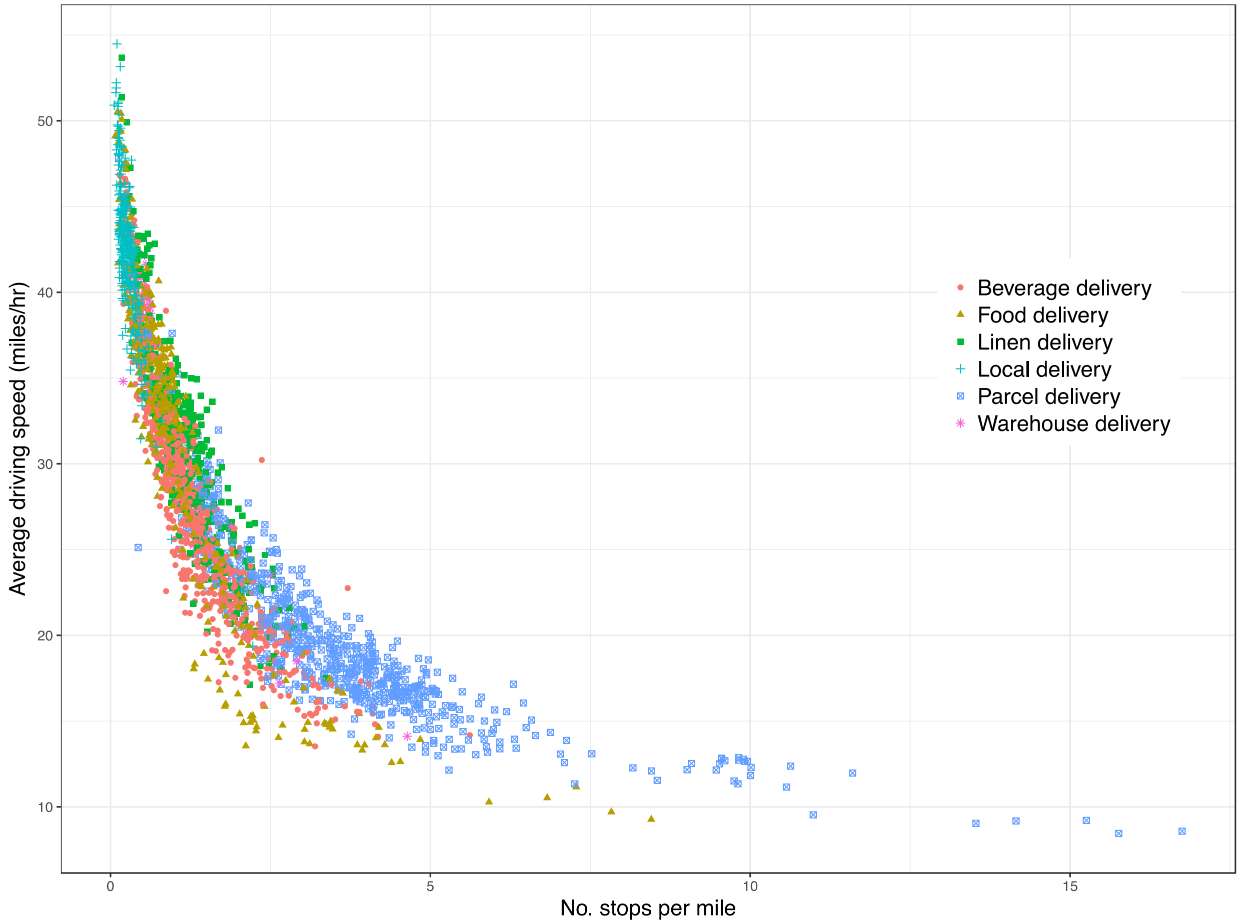
Considering the parcel delivery group, and comparing it with the other delivery fleets, the data (Table 5 and Figure 10) show similar travel patterns, though parcel delivery vehicles stand out by having shorter trips, higher number of stops, and lower driving average speeds. This driving cycle provides an opportunity for electrification and the applicability of regenerative breaking to recover energy from the high number of stops and acceleration.

Table 5. 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 (Walkowicz, 2014)

Figure 10. Stops per mile and average speed for delivery vocations



Source: Own with information from Fleet DNA (Walkowicz, 2014)

Parcel Deliveries

The steady growth of online shopping is attracting more deliveries directly to the customers' homes, therefore in these neighborhoods it is crucial to pursue strategies to reduce pollutant emissions and noise. This section includes the summary statistics and tests performed to the parcel delivery data including their trip length distributions.

The data is aggregated under the two companies or providers (PID 3 and PID 16). The authors determined truck fuel consumption in both fleets through the specific fuel consumption or SFC (O'Keefe et al., 2007) that allows to calculate the fuel consumption of a vehicle when there is no 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 comparing their performance and use it as an input to the TCO analysis. See summary statistics in Table 6.

Table 6. 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										

As expected, the results show that the heavier the vehicle the lower the miles per gallon equivalent, 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%, and classes 6 and 7 are about 40% less efficient. The data show 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%).

One aspect worth of exploring is how companies are using the different vehicle classes and drivetrain technologies to fulfill various trip distances. Specifically, Table 7 shows the pair-wise (two-sample) t-test (unpaired, unequal variance t-test) of hypothesis for equal means of daily distances (DVMT) using different drivetrains (conventional and hybrid) among the two providers independently, and between the two of them.

Overall DVMT patterns for the vehicle class and drivetrain combinations are different; however, in some cases the parcel delivery routes are statistically not differentiable. For example, the routes for classes 4, 5 and 7 for service provider 1 (PID 3) are not statistically different. Moreover, for some of these cases, the delivery patterns are similar between conventional and hybrid vehicles. On the contrary, the routes where class 3 vehicles are used are statistically different from the other classes' routes, and between the different drivetrains. For service provider 2 (PID=16), excluding class 4 and class 6 hybrids, all the other route patterns are statistically different. Finally, while the daily patterns of provider 1 are statistically different from the daily patterns of provider 2 using class 4 vehicles, this is not the case for provider 2 - class 6 vehicles. Ignoring class 3, the daily patterns of the different classes from provider 1, are not statistically different from provider 2 - class 6 routes. The data only contains class 4 and 6 vehicles from provider 2, and the results seem to indicate that this provider chose to use class 6 as a replacement for the larger heavy-duty classes, considering the route structures.

Table 7. Pair-wise t-test of hypothesis

a) Service Provider 1 (PID 3) *

Class		**4**		**5**		**6**		**7**	
	Drive	**0**	**1**	**0**	**1**	**0**	**2**	**0**	**1**
3	**0**	t = 5.4077 p-value = 0.001233	t = 5.513 p-value = 1.736e-07	t = 3.6028 p-value = 0.0009406	t = 6.7071 p-value = 6.8e-10			t = 11.422 p-value < 2.2e-16	t = 3.9897 p-value = 0.0007962
4	**0**		t = -2.8409 p-value = 0.0287	t = -2.8621 p-value = 0.0196	t = -2.9831 p-value = 0.02893			t = -0.48703 p-value = 0.6444	t = -1.9299 p-value = 0.08019
	1			t = -0.4631 p-value = 0.6465	t = -0.067846 p-value = 0.9461			t = 5.9009 p-value = 4.382e-08	t = 0.70014 p-value = 0.4933
5	**0**				t = 0.47473 p-value = 0.6399			t = 4.4346 p-value = 0.0001504	t = 0.93291 p-value = 0.36
	1							t = 8.3128 p-value = 2.911e-14	t = 0.7819 p-value = 0.4482
7	**0**								t = -2.3998 p-value = 0.02984

b) Service Provider 1 (PID 16) *

Class		**4**		**5**		**6**		**7**	
	Drive	**0**	**1**	**0**	**1**	**0**	**2**	**0**	**1**
4	**0**		t = 4.4454 p-value = 2.61e-05			t = 8.4011 p-value = 1.221e-13	t = 4.414 p-value = 2.398e-05		
	1					t = 7.293 p-value = 5.805e-10	t = 1.0202 p-value = 0.3125		
6	**0**						t = -4.7844 p-value = 7.5e-06		

c) Conventional and Hybrids for Service Providers 1 and 2 *

			PID = 16							
	Class		**4**		**5**		**6**		**7**	
		Drive	**0**	**1**	**0**	**1**	**0**	**2**	**0**	**1**
PID = 3	**3**	**0**	t = -2.5329 p-value = 0.01271	t = 2.9365 p-value = 0.003838			t = 8.4088 p-value = 4.105e-13	t = 2.8921 p-value = 0.004966		
	4	**0**	t = -6.3658 p-value = 4.368e-05	t = -4.3798 p-value = 0.0057			t = -0.30875 p-value = 0.7654	t = -3.4497 p-value = 0.008532		
		1	t = -6.0961 p-value = 2.115e-08	t = -3.7275 p-value = 0.0003298			t = 4.2761 p-value = 5.305e-05	t = -1.4541 p-value = 0.1508		
	5	**0**	t = -4.9287 p-value = 4.889e-06	t = -1.9231 p-value = 0.06652			t = 3.8037 p-value = 0.0004084	t = -0.76907 p-value = 0.4458		
		1	t = -6.5212 p-value = 6.168e-09	t = -5.3971 p-value = 1.692e-07			t = 4.9067 p-value = 8.819e-06	t = -1.6033 p-value = 0.1161		
	7	**0**	t = -9.5323 p-value = 2.561e-15	t = -11.621 p-value < 2.2e-16			t = 0.2659 p-value = 0.7911	t = -5.7689 p-value = 3.628e-07		
		1	t = -5.2069 p-value = 6.434e-06	t = -2.6337 p-value = 0.01947			t = 2.2564 p-value = 0.03313	t = -1.613 p-value = 0.1194		

*Note: Drive 0 = Conventional, 1 = Hybrid (parallel or Hydraulic)

With the results from the hypothesis test analyses, the parcel delivery data was aggregated into 5 different groups that shared similar driving patterns. Those groups are shown under the designation of M1, M2, M3, M4 and M5. M1 contains class 3 vehicles, M2 is comprised by class 4, class 6 (from provider 2), and class 7 conventional vehicles, M3 includes class 4 hybrid, and class 5 (from provider 2) conventional and hybrid, M4 includes conventional class 4 and hybrid class 6 from provider 2, and M5 is only class 4 hybrid vehicles from provider 2.

The authors determined trip length probability distribution functions for the 5 groups to help characterize the last mile parcel delivery patterns. The distributions that best fitted the models were Weibull, Gamma, and Lognormal. Table 8 shows the estimated parameters for the various probability distribution functions. Considering the Log-likelihood and the Bayesian and Akaike information criteria, Weibull and Lognormal models seem to provide a better fit, although the criteria differences between the 3 models are very small. These models are relevant for tour-based freight demand modeling exercises along with stops per tour distributions.

Table 8. Trip/Tour length probability distribution functions

		Group				
		M1	M2	M3	M4	M5
Weibull	Shape	2.903836 (0.2285)	1.651192 (0.1003)	3.6594 (0.1840)	1.9907 (0.1367)	3.7343 (0.2564)
	Scale	65.16709 (2.4785)	29.9330 (1.5317)	45.8559 (0.9515)	70.5249 (3.5614)	55.8013 (1.3588)
	Log-likelihood	-410.5725	-645.5764	-753.687	-535.6605	-553.6157
	AIC	825.145	1295.153	1511.374	1075.321	1111.231
	BIC	830.1885	1301.265	1517.899	1080.74	1117.027
Gamma	Shape	7.4791 (1.0784)	2.5208 (0.2677)	11.2764 (1.1311)	3.8297 (0.4927)	9.4940 (1.1396)
	Rate	0.1289 (0.0192)	0.09477 (0.0111)	0.2709 (0.02778)	0.0615 (0.0084)	0.1885 (0.0232)
	Log-likelihood	-407.31	-642.4033	-753.876	-531.2239	-559.6551
	AIC	818.6201	1288.807	1511.752	1066.448	1123.31
	BIC	823.6636	1294.919	1518.277	1071.867	1129.106
Lognormal	Meanlog	3.9920 (0.0388)	3.0697 (0.0532)	3.6837 (0.0228)	3.9949 (0.0504)	3.8655 (0.0300)
	Sdlog	0.3729 (0.02749)	0.6668 (0.0376)	0.3173 (0.01615)	0.5315 (0.0356)	0.3483 (0.02127)
	Log-likelihood	-407.0688	-641.0919	-763.3203	-530.8018	-566.8207
	AIC	818.1377	1286.184	1530.641	1064.604	1137.641
	BIC	823.1813	1292.296	1537.166	1071.023	1143.437

Note: Standard-Error in parenthesis below the parameter coefficients.

Total Cost of Ownership and Lifecycle Assessment

Both companies have a different fleet composition of number of trucks and classes and trip/tour length distributions, Table 9 shows the characteristics of each fleet. In order to compare both providers we assume the same proportion of vehicles by class and drivetrain for two 100-vehicles fleets that would represent each company but using the specific characteristics of their trucks, e.g., miles traveled and fuel consumption.

Table 9. 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)**										

As mentioned, the authors estimated the total cost of ownership using AFLEET 2017 and compared different drivetrain technologies. The results provide a comparison between the two fleets using different drivetrains, i.e. diesel (including renewable and biodiesel), diesel HEV, electric, propane and natural gas. The Appendix at the end of this document, shows the TCO, and incentive efficiency analyses for individual vehicles classes and technologies, using the individual data of the two service providers, and the default values in AFLEET 2017.

Given current public policies (for vehicles and electricity generation) and the state of the art of electric vehicles, EV trucks are a clear pathway for last mile delivery distribution. The study considered nine evaluation scenarios that include monetary incentives and energy efficiency improvements to compare electric trucks with the rest of the other technologies. All cases assume diesel low-NOx engines and the use of ultra-low sulfur diesel.

Modeling Assumptions and Scenarios

General assumptions and scenarios

The TCO assessment is based on the AFLEET 2017 tool and thus the assumptions are consistent with its methodology. However, the author updated some general inputs (e.g., fuel and energy prices) for all analyses and others specific to each scenario.

AFLEET 2017 incorporates several drivetrain technologies but some of them are not available for certain classes or vocations. The study focused the comparison to diesel (including renewable and biodiesel), diesel HEV, electric and natural gas (CNG, LNG) vehicles. As mentioned, the team revised and updated fuel prices, annual VMT and fuel economy values for the analyses. For example, updated fuel prices to April 2018 values keeping consistency with the sources used in AFLEET 2017, and updated fuel economy for the different trucks with the SFC values calculated for the two operators as well as their annual VMT[2]. Fuel prices 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 emissions output, the analyses used the "*Well-to-Wheels Petroleum Use, GHGs, and Air Pollutants*" calculation to account for a more comprehensive environmental impact of not just vehicle operation. Specifically, the authors chose San Francisco, California to reflect the effect on local air pollutants and did not use the "*Diesel In-Use Emissions Multiplier*" option.

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, the authors developed three main modeling scenarios. These scenarios also consider 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 and CALTRANS, 2018). The

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

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 based on several characteristics of use, vocation, and size (e.g., utility cargo van, deliver step van, deliver straight truck). However, to be consistent with the FHWA vehicle classes (e.g., class 3, 4, 5, 8), the authors combined some of the AFLEET categories to create specific classes to reflect the FHWA vehicle class (GWVR).

- 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 prices used were the default ones suggested in AFLEET 2017 since 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 the team kept those default values in the tool. For the classes 3 and 5 vehicle, which required combining two truck types, the researchers averaged their default values. The analyses consider the purchase incentives from HVIP for zero emission vehicles (EV) and hybrid-electric (HEV) to calculate the TCO for the different technologies. Incentives for EV 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 in a case-by-case basis when the companies demonstrate they have a commercial use. For HEV vehicles, 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. Moreover, considering that the actual delivery distances are within the ranges of most vehicle technologies, the analyses assume that the refueling/charging infrastructure would be required at the company's facility.

Table 10 shows a summary of some model parameters for diesel, HEV and EV trucks used in the assessment. The FleetDNA companies only had information about diesel and diesel hydraulic hybrid which were included in the modeling. 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. Therefore, the results reflect fleet analyses, as well as each truck class with the characteristics of both providers and AFLEET assumptions. The results for the vehicle analyses are in the Appendix.

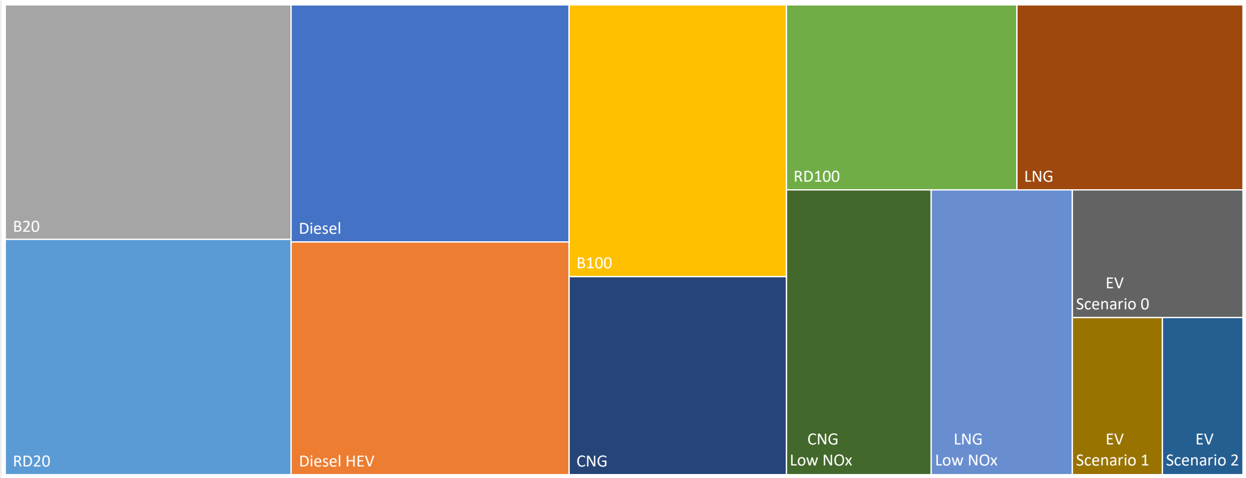
Table 10. Model parameters for diesel and EV trucks

	Purchase Price		**HVIP incentive**		**Annual VMT**		
	Diesel	EV	EV	HEV	AFLEET	PID 3	PID 16
Class 3	$ 55,750	$ 107,250	0	6,000	21,750	18,096	0
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	0
Class 6	$ 75,000	$ 190,000	80,000	15,000	23,000	0	11,044
Class 7	$ 90,000	$ 290,000	90,000	0	65,000	8,809	0
	Maintenance and repair ($/mile)		**Fuel economy (miles per diesel gallon equivalent)**				
	Diesel	EV	AFLEET Diesel	AFLEET EV	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		

Results

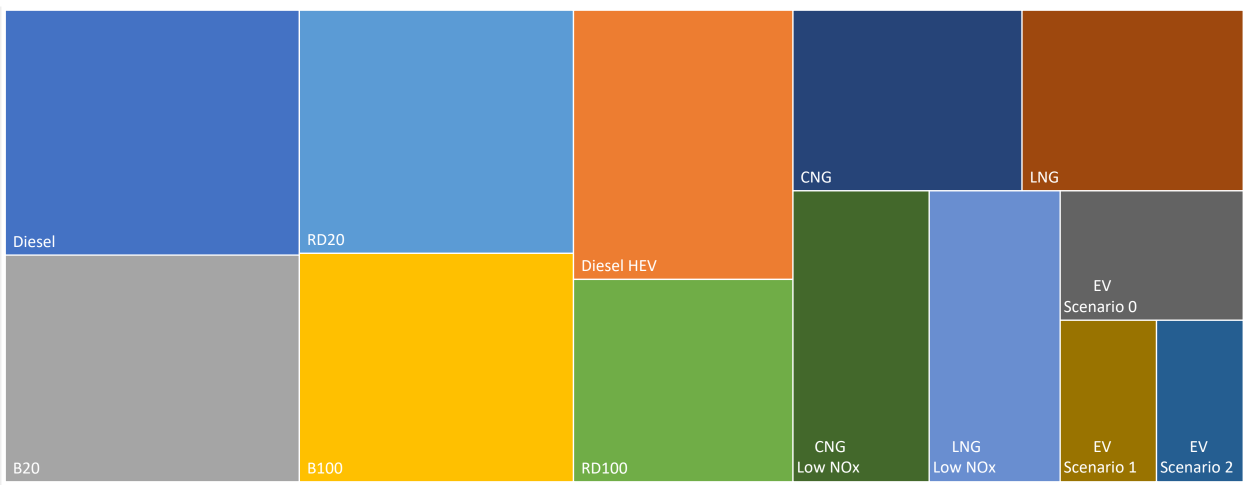
The following section shows the results of the TCO model using AFLEET, for the available technologies. There was no data for hydrogen fuel-cell vehicles because there were no outputs from the model, which is consistent with the current applications, infrastructure and costs of this technology. EVs have the lowest cost of externalities making it the cleanest technology option for both fleets (Figure 11 and Figure 12). 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 11. Total cost of externalities for fleet provider 3



B20>RD20 >Diesel>Diesel HEV>B100>CNG>RD100>LNG>CNG Low NOx>LNG Low NOx>EV Scenario 0>EV Scenario 1 >EV Scenario 2

Figure 12. Total cost of externalities for fleet provider 16



Diesel>B20>RD20>B100>Diesel HEV>RD100>CNG>LNG>CNG Low NOx>LNG Low NOx>EV Scenario 0>EV Scenario 1 >EV Scenario 2

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. Table 11 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 total cost of ownership considering or not externalities.

Table 12 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 considering or not externalities. EV scenario 1 and 2 including externalities are below the diesel in this context.

Table 11. Total cost of externalities for fleet operator 3 (100 vehicles)

PID 3	Total Cost of Ownership	Total cost of Externalities	Total Cost with Externalities
Diesel	$ 28,171,643	$ 3,959,961	$ 32,131,604
Diesel HEV	$ 29,314,695	$ 3,891,832	$ 33,206,527
B20	$ 27,418,186	$ 4,040,727	**$ 31,458,913**
B100	$ 31,542,537	$ 3,551,003	$ 35,093,541
RD20	$ 26,044,533	$ 4,040,688	**$ 30,085,220**
RD100	$ 26,618,116	$ 2,569,940	**$ 29,188,056**
CNG	$ 31,239,370	$ 2,587,110	$ 33,826,480
LNG	$ 67,091,880	$ 2,517,272	$ 69,609,152
EV - Scenario 0	$ 36,239,453	$ 1,306,051	$ 37,545,504
EV - Scenario 1	$ 33,806,738	$ 849,283	$ 34,656,021
EV - Scenario 2	$ 33,328,453	$ 759,480	$ 34,087,933
CNG - Low NOx	$ 31,239,370	$ 2,487,661	$ 33,727,032
LNG - Low NOx	$ 67,091,880	$ 2,417,823	$ 69,509,703

Table 12. Total cost of externalities for fleet operator 16 (100 vehicles)

PID 16	Total Cost of Ownership	Total cost of Externalities	Total Cost with Externalities
Diesel	$ 29,406,171	$ 4,428,275	$33,834,447
Diesel HEV	$ 28,139,878	$ 3,629,959	**$31,769,837**
B20	$ 27,281,570	$ 4,087,713	**$31,369,283**
B100	$ 31,102,066	$ 3,846,866	$34,948,932
RD20	$ 26,009,118	$ 4,087,677	**$30,096,795**
RD100	$ 26,540,443	$ 2,725,285	**$29,265,727**
CNG	$ 31,792,769	$ 2,544,581	$34,337,350
LNG	$ 67,682,069	$ 2,447,327	$70,129,396
EV - Scenario 0	$ 35,109,980	$ 1,457,216	$36,567,195
EV - Scenario 1	$ 32,425,126	$953,106	**$33,378,232**
EV - Scenario 2	$ 31,897,269	$853,995	**$32,751,265**
CNG - Low NOx	$ 31,792,769	$2,431,179	$34,223,948
LNG - Low NOx	$ 67,682,069	$2,333,925	$70,015,994

These results do not account for any incentives for zero-emission vehicles, especially for EV trucks which are shown to have the lowest emissions from all evaluated technologies.

Considering the benefits of EV 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, the authors used two metrics, the return of investment (ROI) of each dollar of incentive invested and its corresponding dollars of externalities reduced. The inverse, or cost of abatement, indicates the cost (in dollar incentives) to reduce one dollar of externalities.

For the case of the first fleet company (Figure 13), the use of the HVIP voucher makes the EV 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 reduction gain is not that high.

It is only with both incentives policies and efficiency gains that the EV fleet's TCO can compete with a diesel fleet when considering externalities. Scenario 2 with HVIP is almost at the break-even point with diesel and it seems that the additional gain from LCFS is not 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 10, the data for this operator indicates that the annual VMT for the vehicles is low.

Figure 14 show 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 (and 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 EV 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 gain in externalities in scenario 2, making the LCFS incentive not as efficient for this case.

Figure 13. TCO results for PID 3

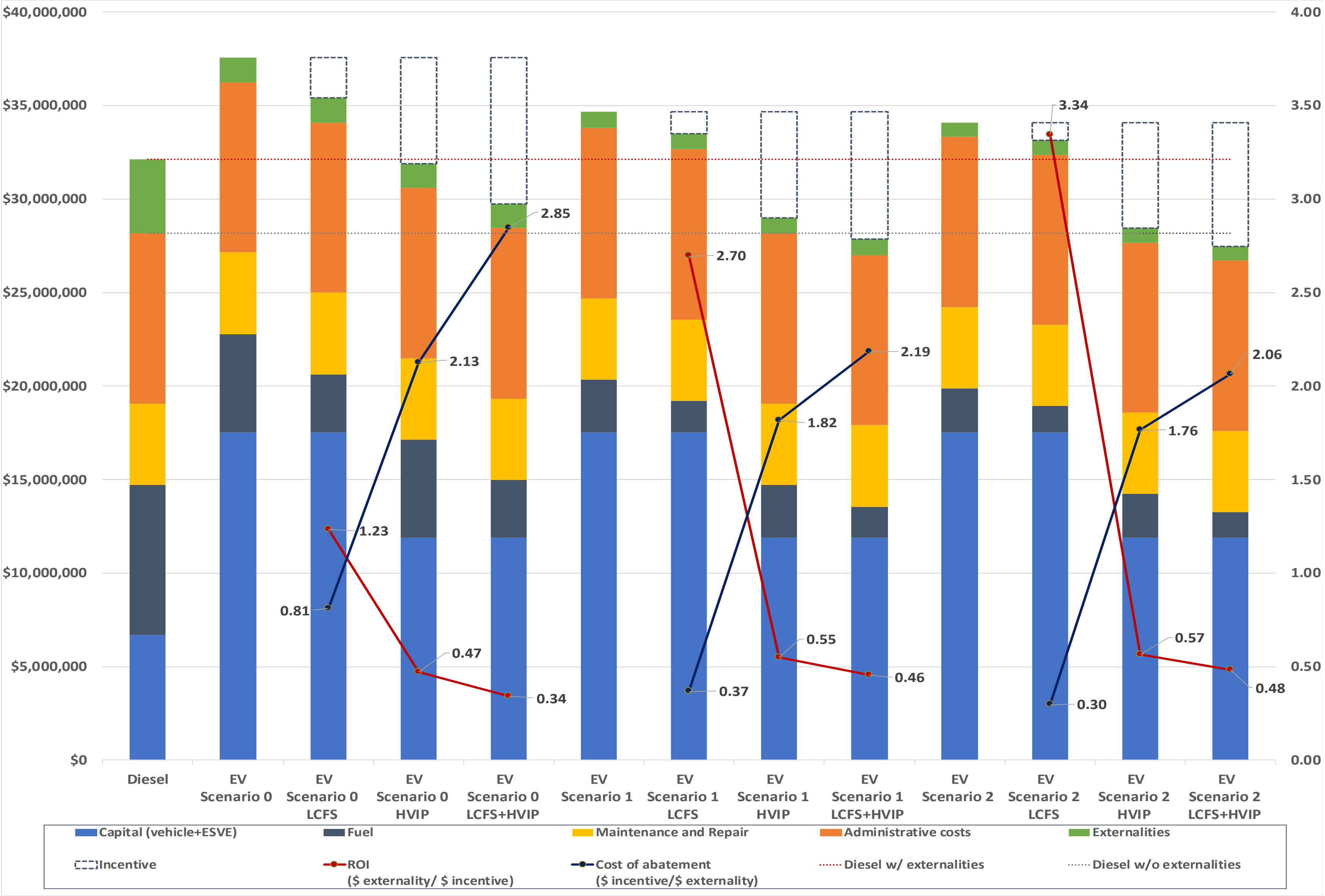
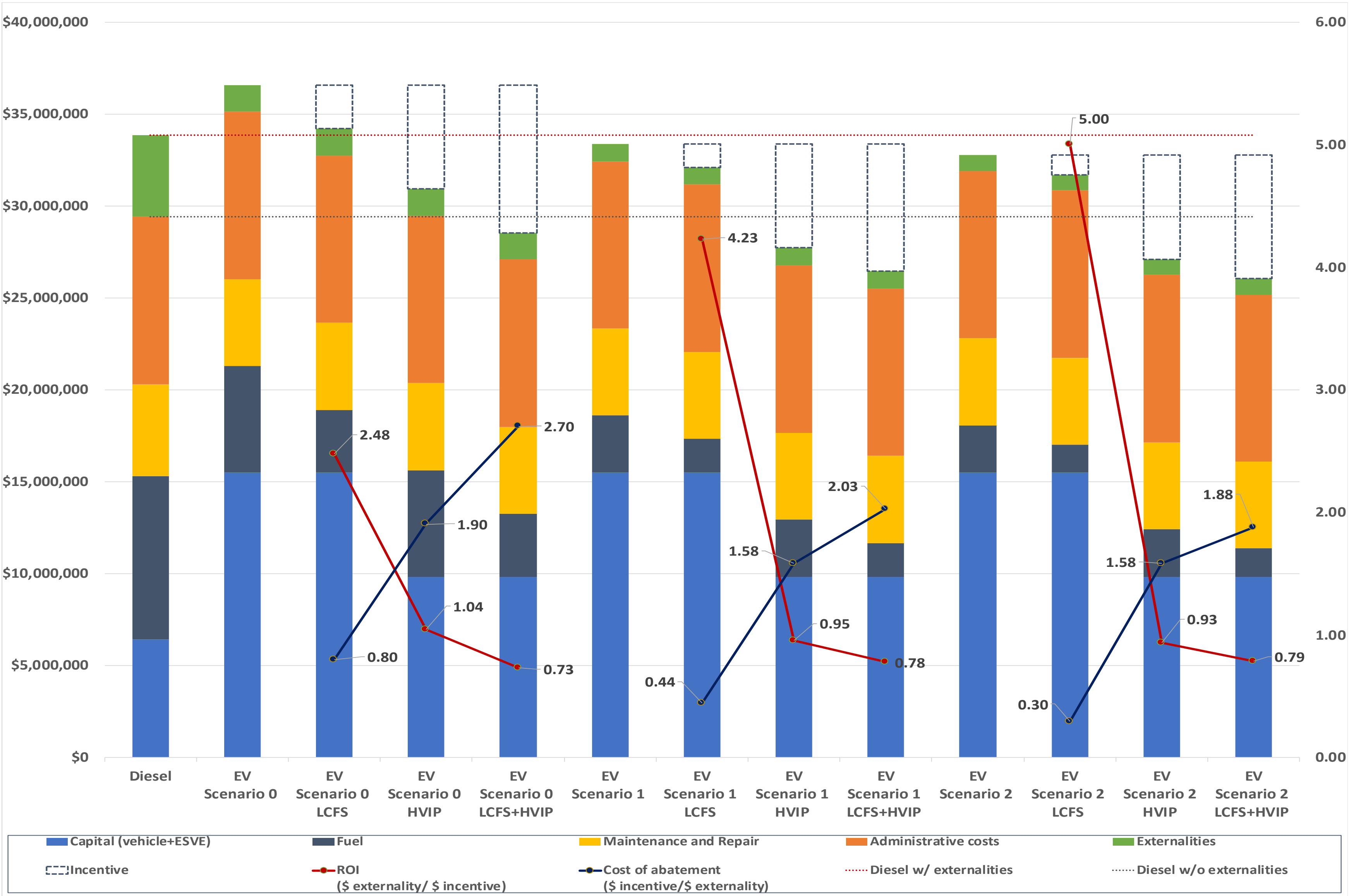


Figure 14. TCO results for PID 16



Analyzing the individual class vehicles, Table 13 shows the payback periods for provider 3, 16 and those using AFLEET default values. 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 for annual mileage and other factors, 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 VMT values, in average, are higher than those found in the two parcel fleet operators. Consequently, many of the results from the empirical data are not as bright as the ones using the AFLEET default values.

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

Figure 15 shows the impact of different levels of HVIP purchase incentive for a class 5 truck (using fleet provider 3 annual VMT). The current HVIP voucher for a class 5 truck is $80,000 resulting in a 12 years payback 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.

The authors also conducted a sensitivity analysis for nine of the main parameters in 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 charging infrastructure (ESVE). All parameters, except ESVE were tested under a change of -100% to 200% from their baseline values (i.e., those in AFLEET 2017 except for updated fuel costs). The analyses examined charging infrastructure a range of -100% to 1000% to account for the additional costs associated with installation and grid upgrades that many other studies neglect.

Purchase price, electricity cost and VMT are the top parameters affecting the total cost of ownership of these vehicles (see Figure 16). Consistent with previous results, purchase incentives are critical for making these technologies competitive against conventional ones. 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. This difference has a major impact on the TCO and payback periods.

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[3] 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 EV

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

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)[4].

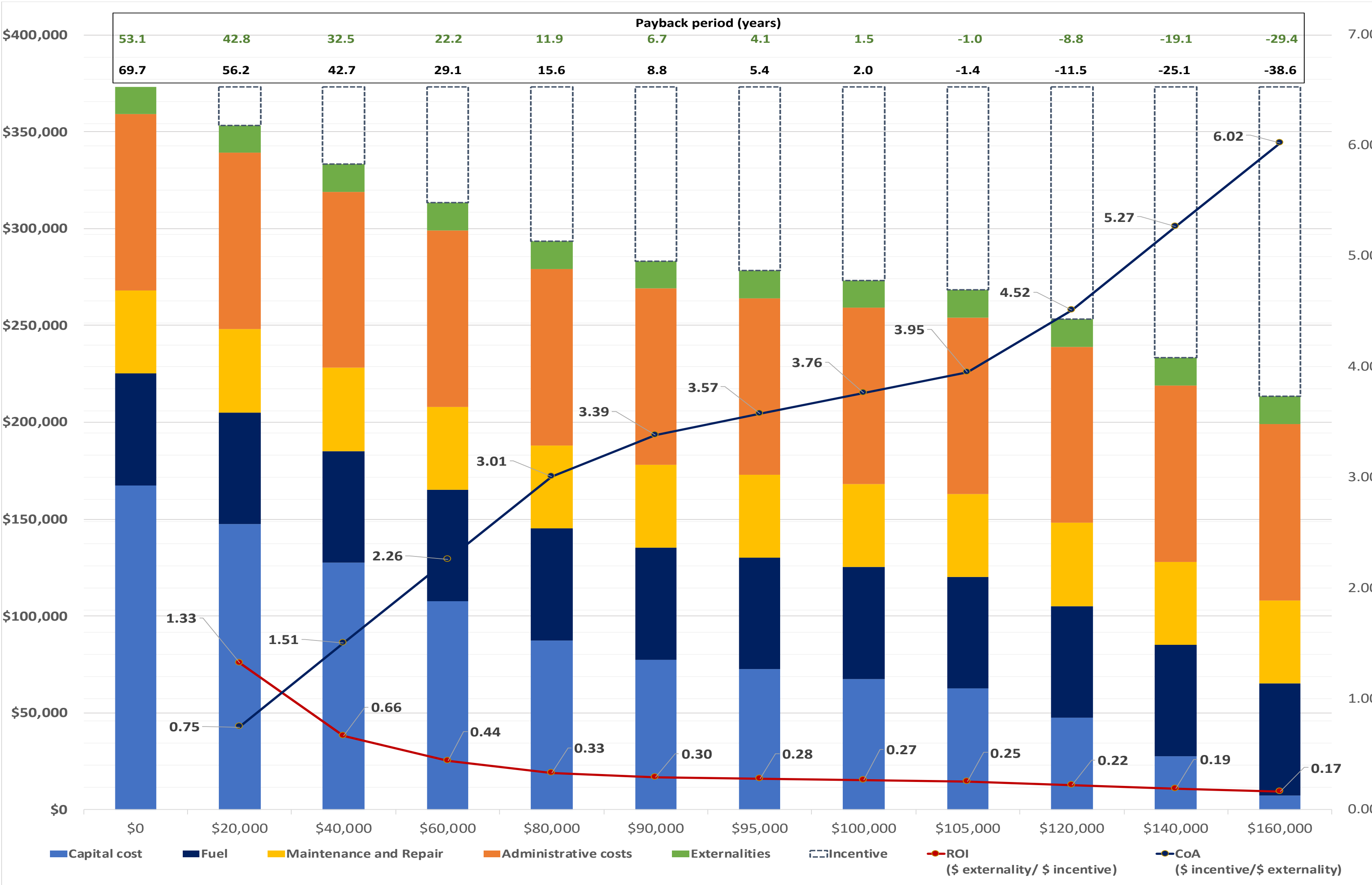
[4] http://www.cpuc.ca.gov/sb350te/

Table 13. 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	

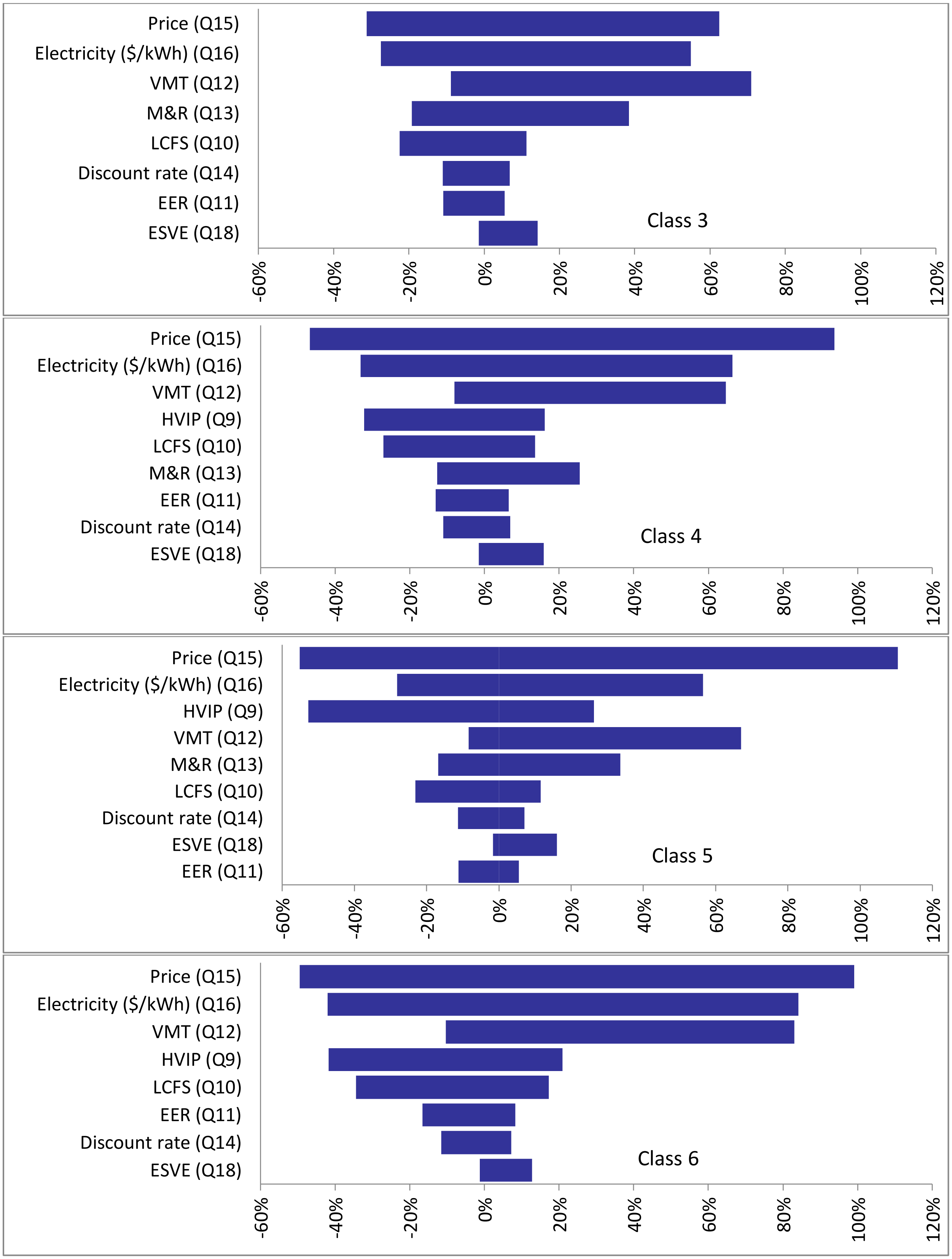
*Note: For each truck class payback with externalities is shown in the first row, and for payback without externalities in the second row

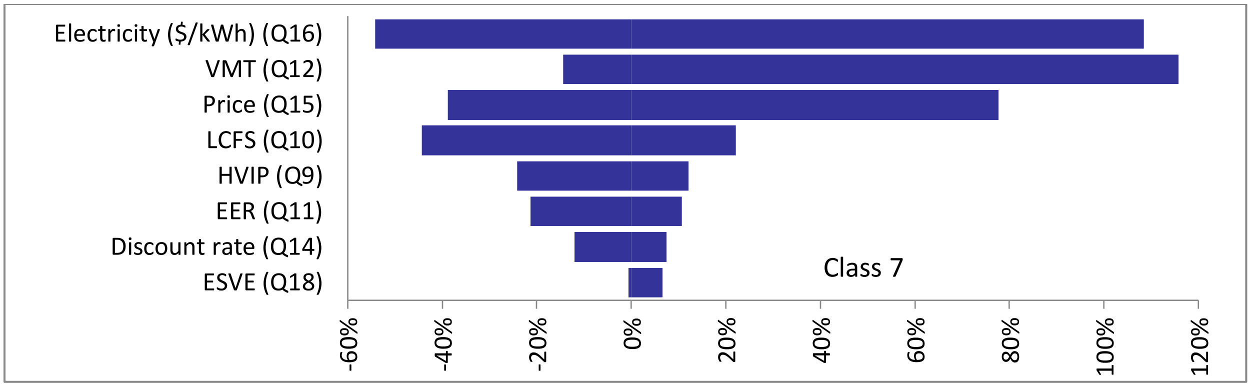
Figure 15. Different incentive impact for class 5 truck PID 3



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

Figure 16. Sensitivity analysis for electric trucks. Percent change in TCO for classes 3-7





Note: All parameters vary from -100% to 200%, except for ESVE that goes from -100% to 10,000%

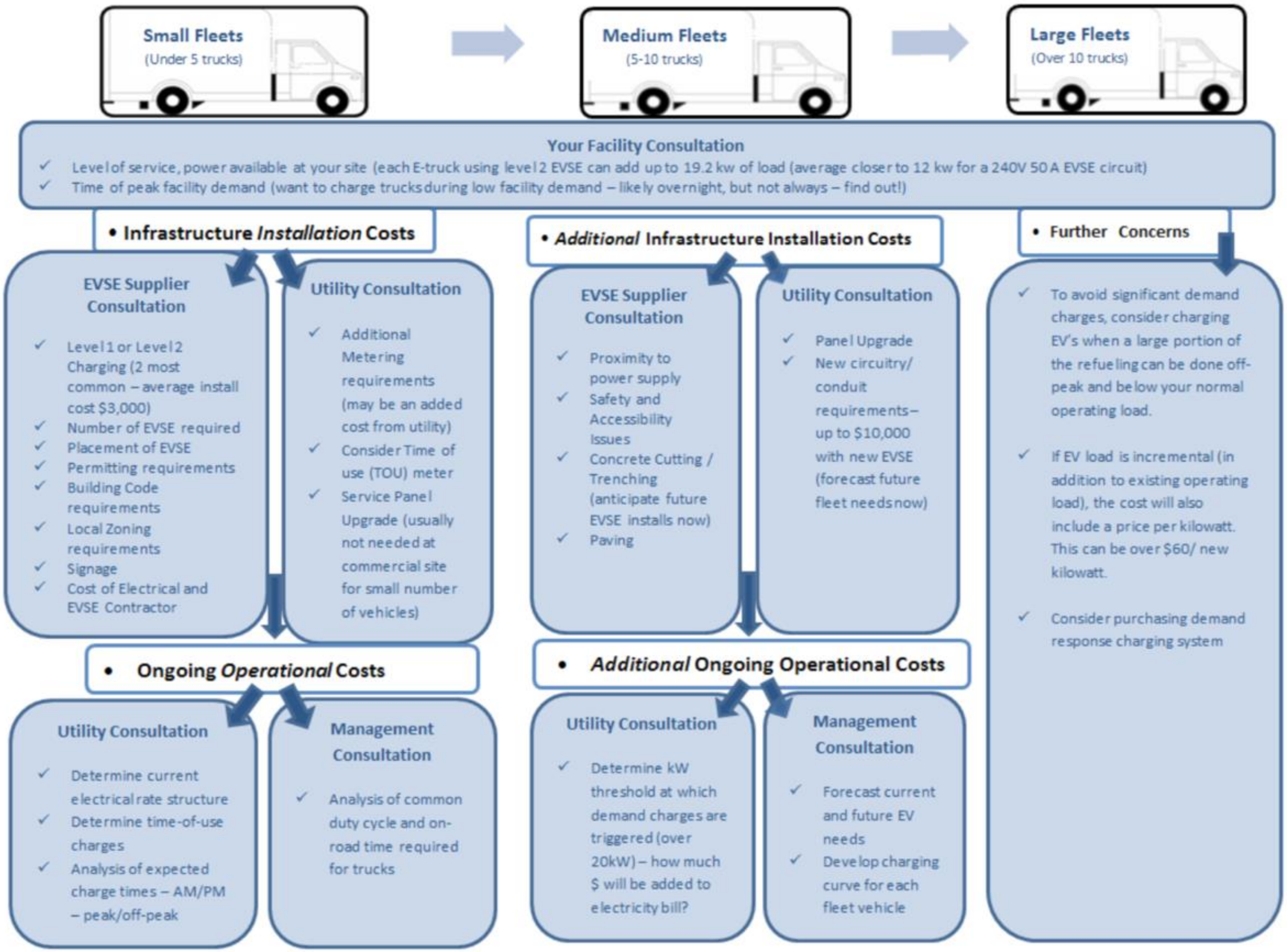
Additional Considerations for Charging Infrastructure (ESVE)

Several pilots have pointed out the need for additional charging infrastructure investments, which are usually not considered when planning for EV truck fleet conversion. From the sensitivity analysis above, if charging infrastructure costs were 10 times higher, the TCO impact would represent less than 20% of all the costs.

Some key points to consider in advance when installing or upgrading EVSE are, additional charging infrastructure and grid upgrades costs, landlord permits, vehicle charging time and vehicle operations and maintenance (Quak et al., 2016a; Quak et al., 2016b).

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, use of battery over time (charge and discharge), and ESVE infrastructure (Quak et al., 2016a; Quak et al., 2016b). As mentioned, in the European pilots, the participating companies showed that depot-charging was a viable option; however, considering the depot and yard, and the operations performed with and to the vehicles, one charger per vehicle is often required. Usually, this is performed overnight, while other logistics operations are conducted at the facilities; as result, retrofits to the electric infrastructure at the facility and the grid may be needed. CalHEAT and CALSTART (2013) developed common guidelines according to the size of the fleet that provide additional information of studies and steps to be considered when switching to EV trucks. Figure 17 shows these guidelines.

Figure 17. Infrastructure planning guidelines for EV truck fleets



Source: (CalHEAT and CALSTART, 2013)

Conclusions

Empirical data from different last mile delivery fleets show 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. Moreover, 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 technically compete with conventional diesel trucks. However, electric trucks pose themselves not only as a technically feasible alternative but the cleanest one (considering the California grid) with noise reduction benefits and lower maintenance costs. Nonetheless, purchase cost, payback period, and uncertain infrastructure costs are key factors that fleet operators analyze when considering to transition to cleaner vehicles.

The fleet driving data shows that parcel delivery trucks are traveling less miles than expected (e.g., AFLEET values) and this has an important impact in the payback periods.

Parcel deliveries are a growing component of urban freight distribution, especially because of the increase of the on-demand economy. The tour distance analyses, which are consistent with the empirical findings in Europe, show that the daily distances are in general shorter than 100 miles. Consistent with previous findings, the authors conclude that comprehensive evaluations of zero-emission vehicles in freight applications should be considered. This is because the benefits (environmental performance and lower operational costs) of adopting these technologies are usually not valued as much as their costs (higher purchase cost, EVSE).

The empirical results show that different technology scenarios for EVs with a combination of improved efficiency factors and monetary incentives make this technology competitive with diesel drivetrains. However, the results also evidence the critical role of financial incentives. The analyses also showed the different results when considering or not considering externalities. Although a total cost of ownership with a life-cycle assessment is important, fleet managers might pay more attention to their of pocket expenses (which may not include the externalities). On the other hand, agency regulations bring the attention to externalities and a system-wide scope.

The study also analyzed the TCO for individual truck classes. The sensitivity analyses showed that vehicle miles traveled, purchase price and electricity cost are the main factors in the lifetime cost of an EV truck. As mentioned before, the empirical data showed that the fleets operate the vehicles less annual miles than expected (e.g. compared to AFLEET parameters) which greatly affects the payback periods. The other relevant factors related to vehicle price and electricity are directly affected by HVIP purchase voucher and the LCFS credit; without them, EVs are only competitive with diesel trucks if there is a large efficiency improvement (EER) and they are used for more annual miles than empirically found. The scenarios that only considered the LCFS credit showed a lower cost of abatement than those with the HVIP incentive; though in some cases the LCFS credit is not enough to make EVs comparable to their diesel counterparts. Nevertheless, the results show the importance of this credit scheme.

Therefore, last mile and specifically parcel fleets require these incentives to adopt zero-emission vehicles. However, a more thorough study is needed to improve the efficiency of the incentives available. The cost of abatement (externalities) combining both incentives could show marginal benefits compared to diesel trucks. The authors expect to deepen on this matter to provide better tools for public policy design.

Likewise, pilot programs will inform better about the needs of commercial fleets and vehicles operating in the U.S. For instance, smaller fleets, face important challenges in securing the adequate charging infrastructure, not just upfront costs relative to grid upgrade but even some space constraints (small depots), could have a negative impact in the adoption of EVs (Feng and Figliozzi, 2012; Davis and Figliozzi, 2013; Lebeau et al., 2016).

In summary, zero and near-zero emission technologies are a viable option for some delivery vocations to improve the sustainability of urban freight systems. However, the benefits from these technologies concentrate on emission reductions, and they are not necessarily the solution for other problems such as congestion, parking management, infrastructure management or safety. For instance, the tanks used in gas-powered vehicles add to the weight of the vehicle, which could affect the pavement and roadway infrastructures. Incentives play a fundamental role in making a successful business case for operators in supporting upfront costs of vehicles and charging infrastructure investments.

Improvements need both, operational improvements in the last mile distribution along with zero or near zero emission technologies. Technology is one of the tools in the menu of strategies to improve the system, and should not be the only option. Programmatic freight demand management and land use planning strategies could also help improve urban freight deliveries.

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Appendix

Figure 18. TCO for class 3 EV - AFLEET

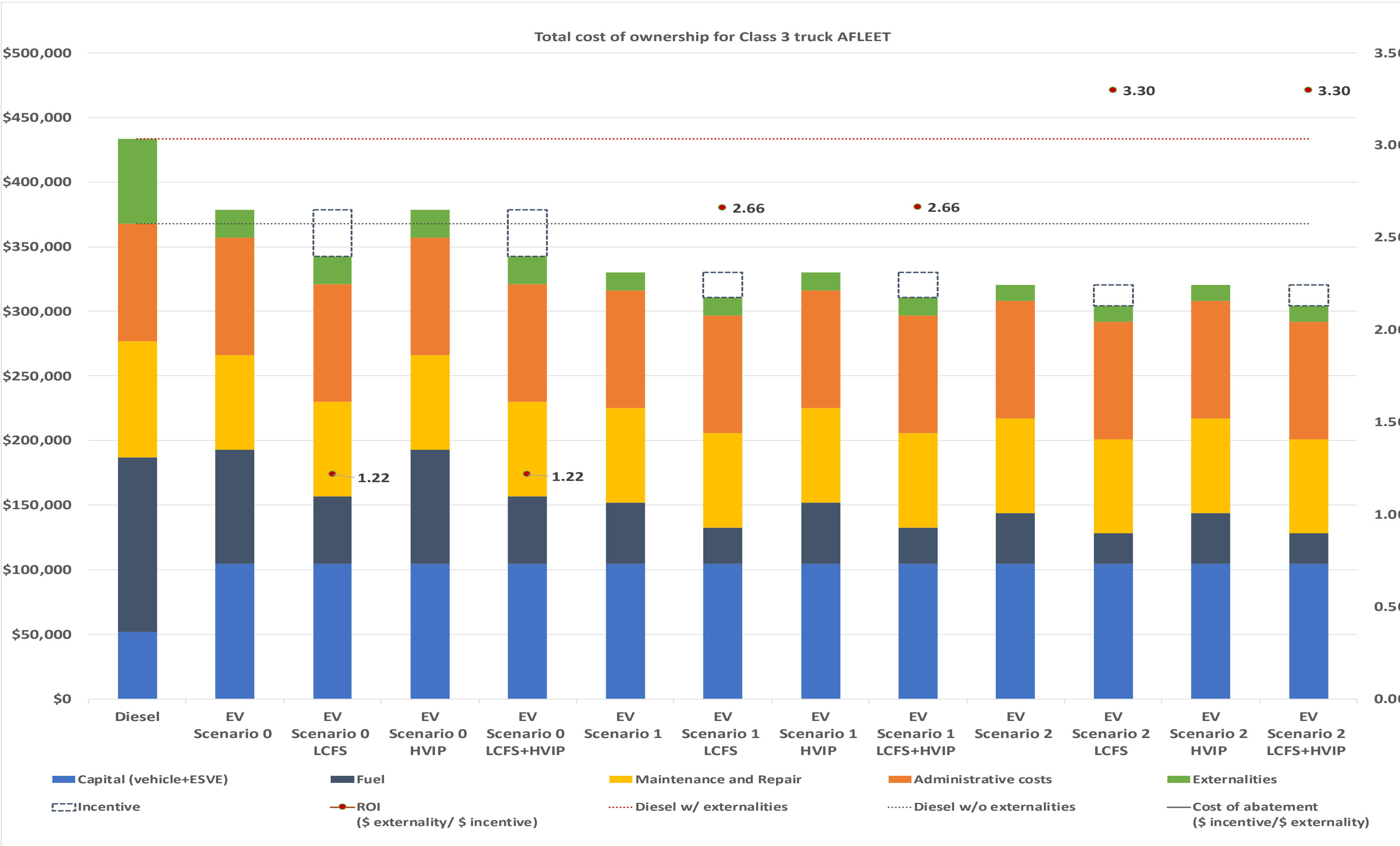


Figure 19. TCO for class 3 EV – PID 3

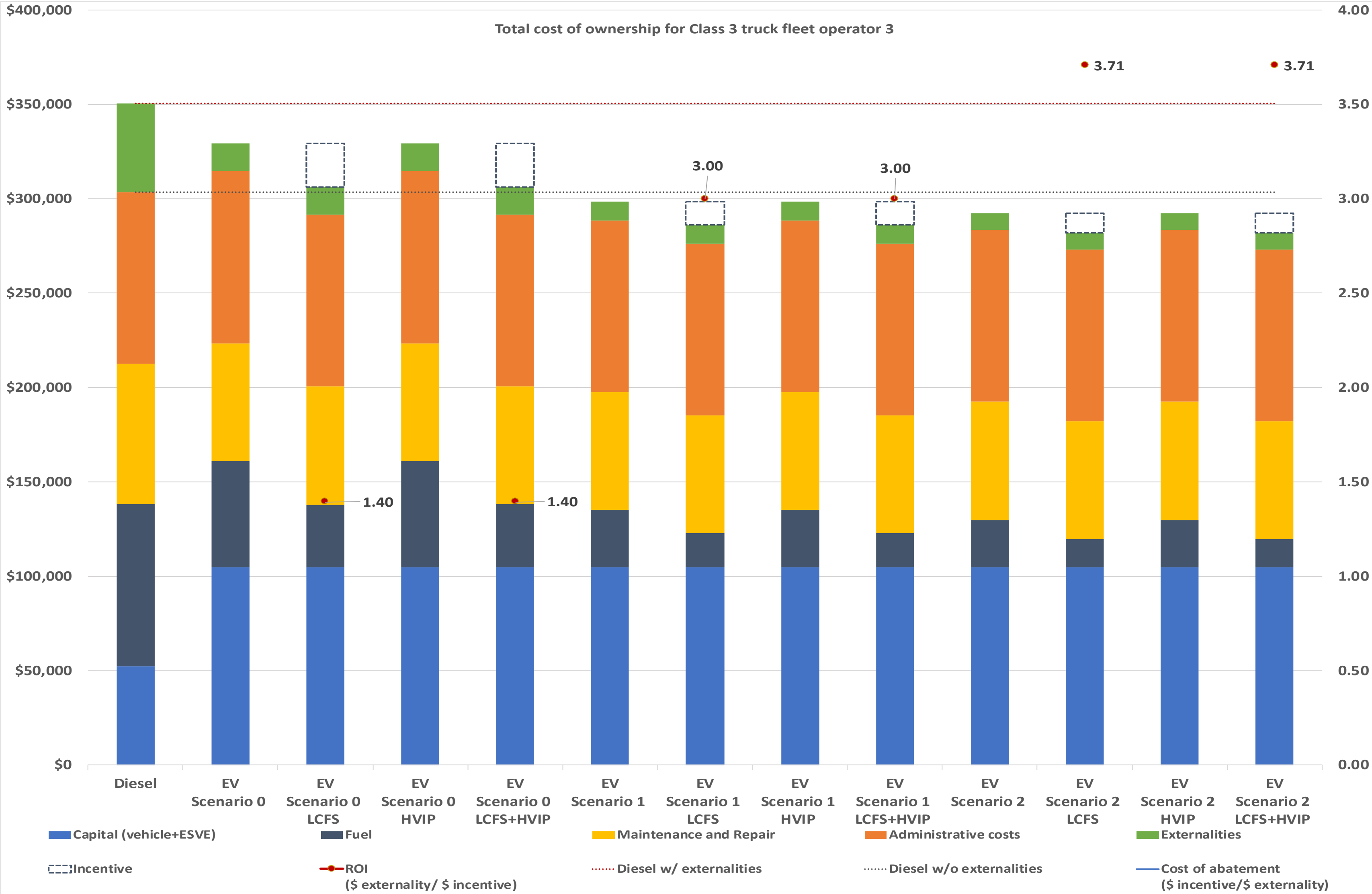
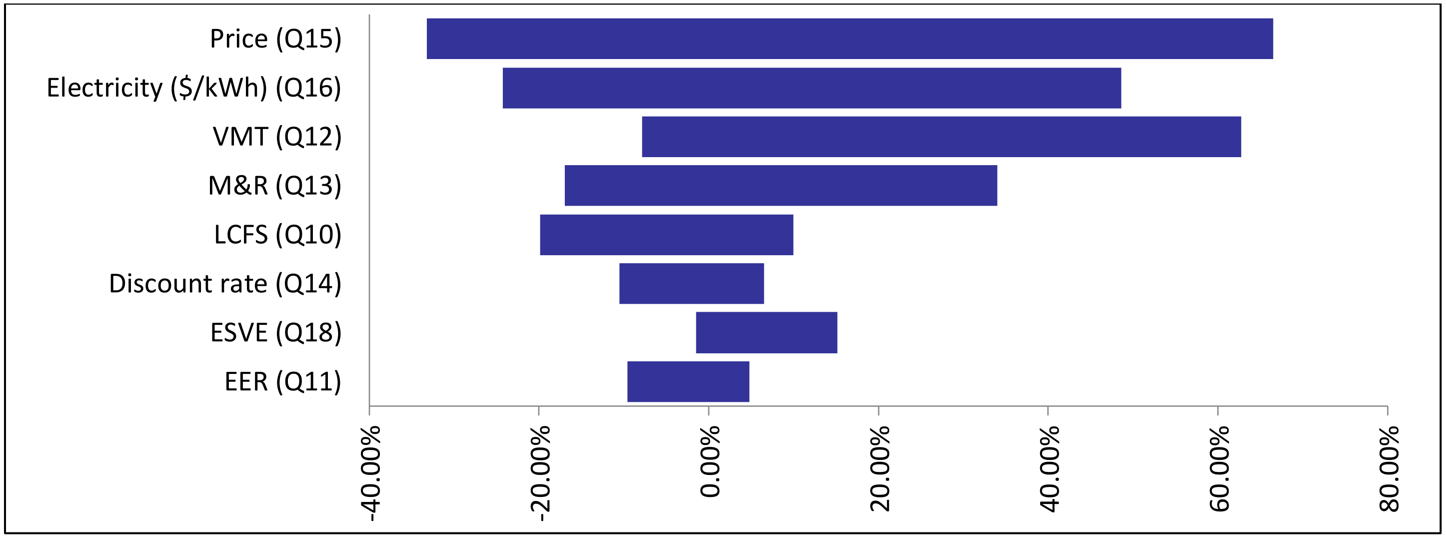


Figure 20. Percent change in TCO for class 3 EV - PID 3



Note: All parameters vary from -100% to 200%, except for ESVE that goes from -100% to 10,000%

Table 14. Summary scenarios for different technologies for class 3 truck - AFLEET

Summary scenarios different technologies AFLEET - Class 3	Diesel	Diesel HEV	Diesel HEV HVIP	B20	B100	RD20	RD100	CNG	LNG	CNG Low NOx	LNG Low NOx
Incentive	$0	$0	$6,000	$0	$0	$0	$0	$0	$0	$0	$0
Capital (vehicle+ESVE)	$52,129	$66,856	$61,245	$52,129	$52,129	$52,129	$52,129	$84,939	$222,873	$84,939	$222,873
Fuel	$132,209	$106,563	$106,563	$99,886	$158,010	$80,527	$88,610	$80,768	$142,887	$80,768	$142,887
Diesel Exhaust Fluid	$2,884	$2,325	$2,325	$2,884	$2,884	$2,884	$2,884	$0	$0	$0	$0
Maintenance and Repair	$89,482	$67,122	$67,122	$89,482	$89,482	$89,482	$89,482	$93,432	$275,816	$93,432	$275,816
Insurance	$82,331	$82,331	$82,331	$82,331	$82,331	$82,331	$82,331	$82,331	$82,331	$82,331	$82,331
License and Registration	$8,672	$8,672	$8,672	$8,672	$8,672	$8,672	$8,672	$8,672	$8,672	$8,672	$8,672
Total Cost of Ownership	$367,707	$333,868	$328,257	$335,383	$393,508	$316,024	$324,108	$350,141	$732,579	$350,141	$732,579
Petroleum Use (barrels)	769	620	620	623	35	622	34	4	11	4	11
GHGs (short tons)	436	352	352	371	111	371	112	436	485	436	485
CO (lbs)	595	337	337	611	674	611	671	4,555	4,418	4,555	4,418
NOx (lbs)	978	922	922	992	1,046	991	1,042	592	475	523	406
PM10 (lbs)	109	105	105	111	117	111	118	100	102	100	102
PM2.5 (lbs)	36	33	33	38	44	38	45	28	32	28	32
VOC (lbs)	135	122	122	164	277	161	265	170	143	170	143
SOx (lbs)	191	154	154	211	289	205	260	195	163	195	163
Total cost of Externalities	$65,464	$57,834	$57,834	$60,283	$55,660	$60,283	$39,555	$39,405	$40,230	$37,776	$38,601
Total Cost with Externalities	$433,171	$391,702	$386,092	$395,666	$449,168	$376,307	$363,663	$389,546	$772,809	$387,917	$771,180

Note: Values in green represent a cost lower than diesel BAU

Table 15. Summary scenarios for different technologies for class 3 truck - PID 3

Summary scenarios different technologies PID 3 - Class 3	Diesel	Diesel HEV	Diesel HEV HVIP	B20	B100	RD20	RD100	CNG	LNG	CNG Low NOx	LNG Low NOx
Incentive	$0	$0	$6,000	$0	$0	$0	$0	$0	$0	$0	$0
Capital (vehicle+ESVE)	$52,129	$66,856	$61,245	$52,129	$52,129	$52,129	$52,129	$83,754	$222,671	$83,754	$222,671
Fuel	$84,105	$88,660	$88,660	$83,104	$131,464	$66,998	$73,723	$67,199	$118,881	$67,199	$118,881
Diesel Exhaust Fluid	$1,835	$1,934	$1,934	$2,400	$2,400	$2,400	$2,400	$0	$0	$0	$0
Maintenance and Repair	$74,449	$55,845	$55,845	$74,449	$74,449	$74,449	$74,449	$78,830	$262,888	$78,830	$262,888
Insurance	$82,331	$82,331	$82,331	$82,331	$82,331	$82,331	$82,331	$82,331	$82,331	$82,331	$82,331
License and Registration	$8,672	$8,672	$8,672	$8,672	$8,672	$8,672	$8,672	$8,672	$8,672	$8,672	$8,672
Total Cost of Ownership	$303,520	$304,297	$298,687	$303,084	$351,443	$286,977	$293,703	$320,786	$695,443	$320,786	$695,443
Petroleum Use (barrels)	489	516	516	518	29	518	29	4	10	4	10
GHGs (short tons)	278	293	293	309	92	309	93	363	403	363	403
CO (lbs)	470	280	280	508	561	508	558	3,789	3,676	3,789	3,676
NOx (lbs)	757	767	767	825	871	825	867	492	395	435	338
PM10 (lbs)	87	88	88	92	98	92	98	83	85	83	85
PM2.5 (lbs)	27	28	28	31	36	32	38	23	27	23	27
VOC (lbs)	99	101	101	136	231	134	221	141	119	141	119
SOx (lbs)	121	128	128	175	241	170	216	162	136	162	136
Total cost of Externalities	$46,763	$48,118	$48,118	$50,155	$46,309	$50,155	$32,910	$32,785	$33,471	$31,429	$32,116
Total Cost with Externalities	$350,283	$352,415	$346,805	$353,239	$397,752	$337,132	$326,613	$353,571	$728,914	$352,215	$727,559

Note: Values in green represent a cost lower than diesel BAU

Figure 21. TCO for Class 4 EV - AFLEET

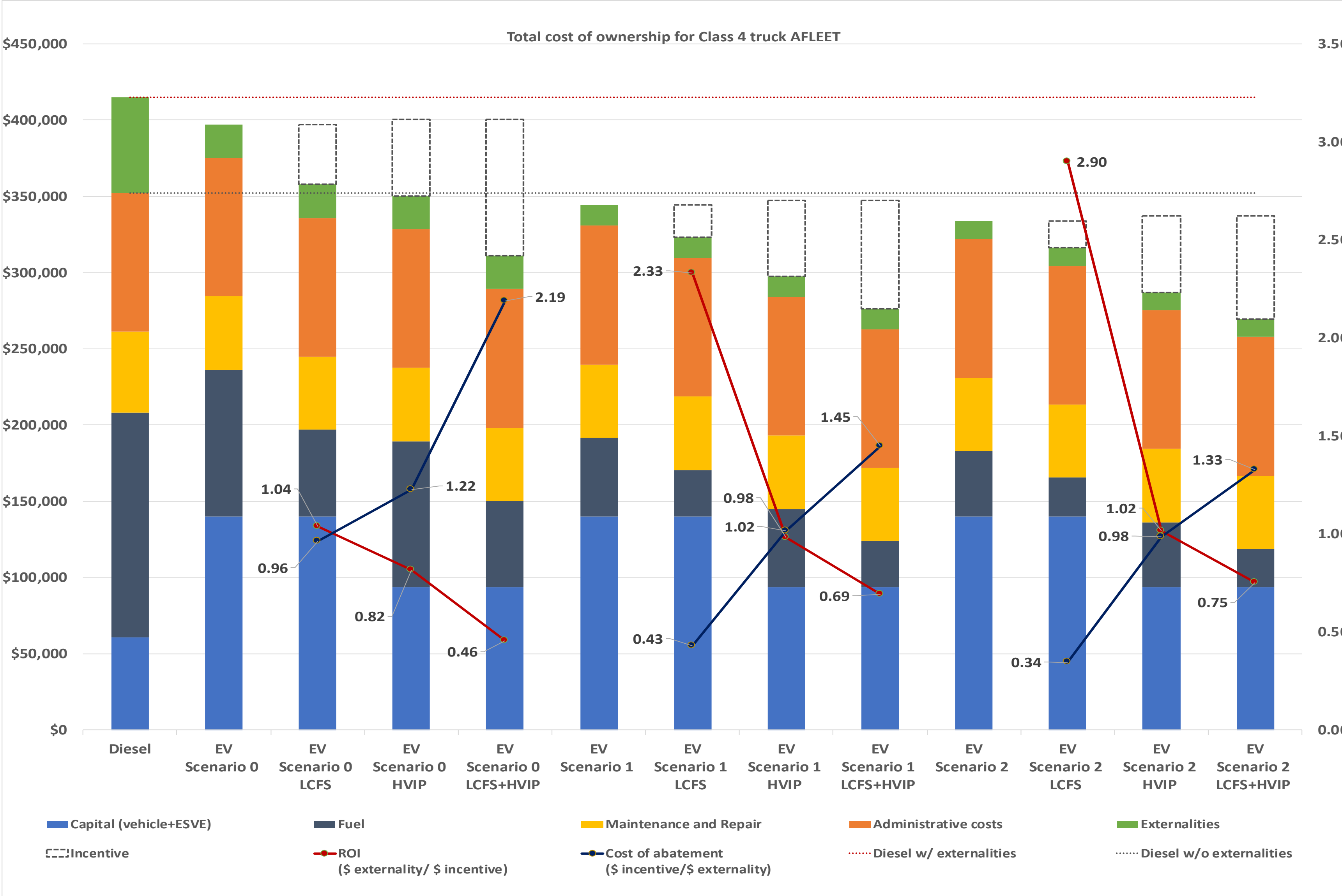


Figure 22. TCO for class 4 EV – PID 3

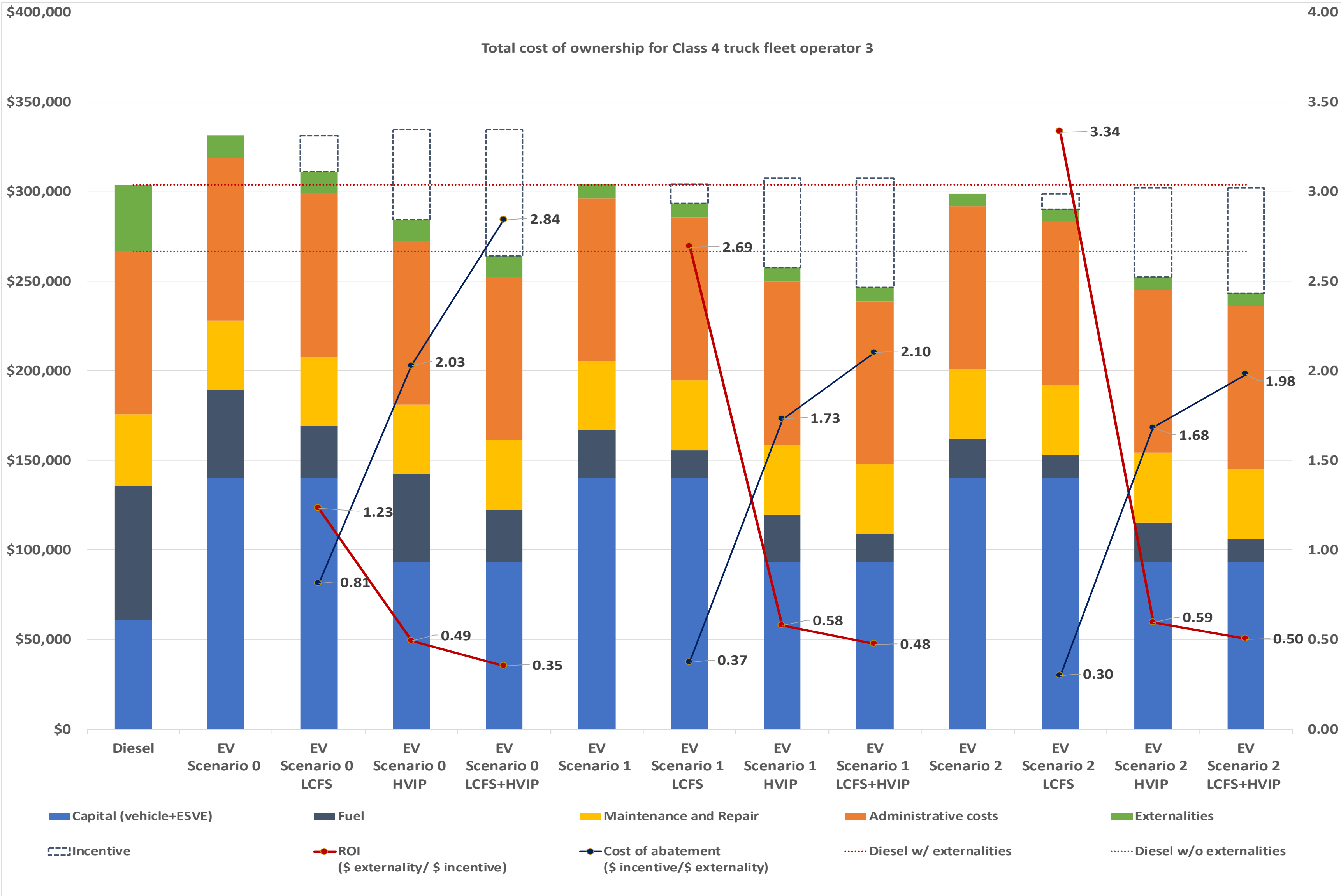
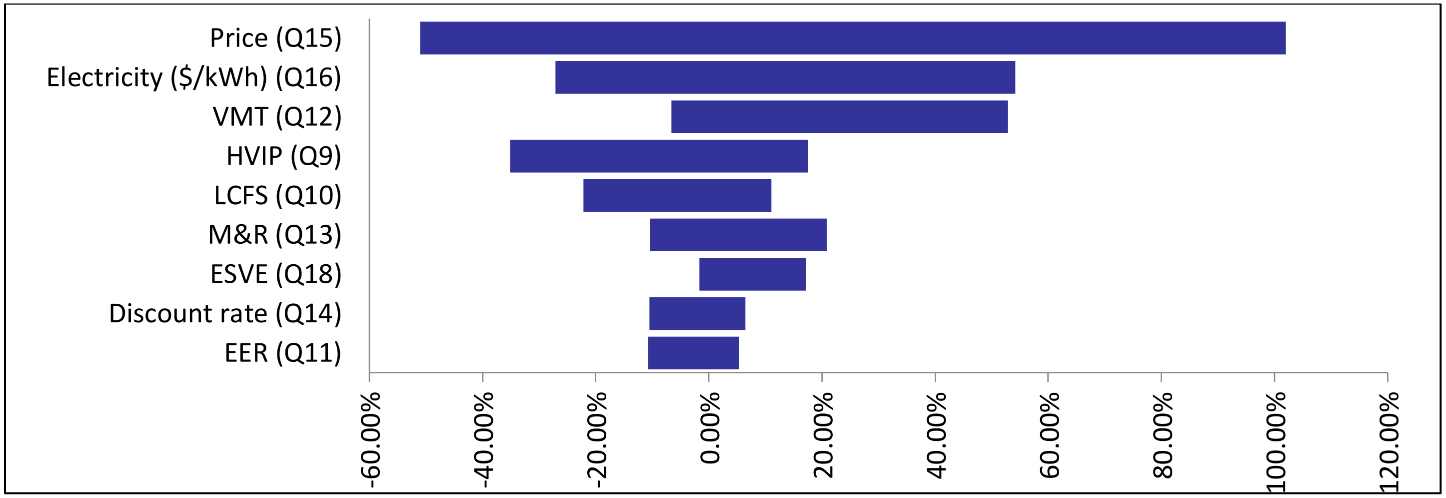
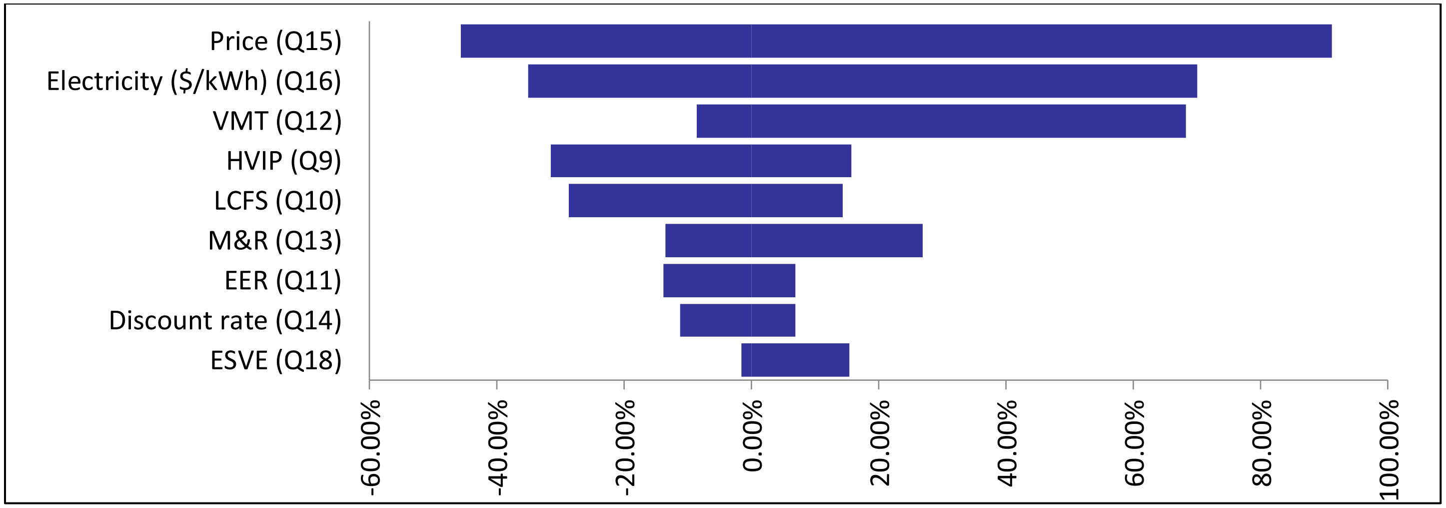


Figure 23. Percent change in TCO for class 4 EV – PID 3



Note: All parameters vary from -100% to 200%, except for ESVE that goes from -100% to 10,000%

Figure 24. Percent change in TCO for class 4 EV – PID 16



Note: All parameters vary from -100% to 200%, except for ESVE that goes from -100% to 10,000%

Table 16. Summary scenarios for different technologies for class 4 truck - AFLEET

Summary scenarios different technologies AFLEET - Class 4	Diesel	Diesel HEV	Diesel HEV HVIP	B20	B100	RD20	RD100	CNG	LNG	CNG Low NOx	LNG Low NOx
Incentive	$0	$0	$15,000	$0	$0	$0	$0	$0	$0	$0	$0
Capital (vehicle+ESVE)	$60,778	$77,609	$63,583	$60,778	$60,778	$60,778	$60,778	$110,704	$248,460	$110,704	$248,460
Fuel	$144,005	$113,390	$113,390	$108,798	$172,109	$87,712	$96,516	$84,039	$136,056	$84,039	$136,056
Diesel Exhaust Fluid	$3,142	$2,474	$2,474	$3,142	$3,142	$3,142	$3,142	$0	$0	$0	$0
Maintenance and Repair	$53,257	$41,864	$41,864	$53,257	$53,257	$53,257	$53,257	$72,964	$257,741	$72,964	$257,741
Insurance	$82,331	$82,331	$82,331	$82,331	$82,331	$82,331	$82,331	$82,331	$82,331	$82,331	$82,331
License and Registration	$8,672	$8,672	$8,672	$8,672	$8,672	$8,672	$8,672	$8,672	$8,672	$8,672	$8,672
Total Cost of Ownership	$352,185	$326,339	$312,313	$316,977	$380,288	$295,891	$304,696	$358,710	$733,260	$358,710	$733,260
Petroleum Use (barrels)	838	660	660	678	38	678	37	5	11	5	11
GHGs (short tons)	475	374	374	404	121	405	122	454	461	454	461
CO (lbs)	494	287	287	511	580	510	576	3,563	3,399	3,563	3,399
NOx (lbs)	838	771	771	852	912	852	907	586	432	534	380
PM10 (lbs)	89	84	84	91	98	91	99	79	80	79	80
PM2.5 (lbs)	33	29	29	34	41	35	43	23	27	23	27
VOC (lbs)	126	110	110	157	281	154	267	163	127	163	127
SOx (lbs)	208	164	164	229	315	223	283	203	155	203	155
Total cost of Externalities	$62,666	$53,558	$53,558	$57,023	$46,600	$57,022	$34,445	$37,648	$36,005	$36,412	$34,769
Total Cost with Externalities	$414,851	$379,897	$365,872	$374,000	$426,888	$352,913	$339,142	$396,358	$769,264	$395,122	$768,028

Note: Values in green represent a cost lower than diesel BAU

Table 17. Summary scenarios for different technologies for class 4 truck - PID 3

Summary scenarios different technologies PID 3 - Class 4	Diesel	Diesel HEV	Diesel HEV HVIP	B20	B100	RD20	RD100	CNG	LNG	CNG Low NOx	LNG Low NOx
Incentive	$0	$0	$15,000	$0	$0	$0	$0	$0	$0	$0	$0
Capital (vehicle+ESVE)	$60,778	$77,609	$63,583	$60,778	$60,778	$60,778	$60,778	$107,106	$247,818	$107,106	$247,818
Fuel	$73,367	$57,769	$57,769	$55,430	$87,685	$44,687	$49,173	$42,816	$69,317	$42,816	$69,317
Diesel Exhaust Fluid	$1,601	$1,260	$1,260	$1,601	$1,601	$1,601	$1,601	$0	$0	$0	$0
Maintenance and Repair	$39,958	$31,410	$31,410	$39,958	$39,958	$39,958	$39,958	$54,153	$242,643	$54,153	$242,643
Insurance	$82,331	$82,331	$82,331	$82,331	$82,331	$82,331	$82,331	$82,331	$82,331	$82,331	$82,331
License and Registration	$8,672	$8,672	$8,672	$8,672	$8,672	$8,672	$8,672	$8,672	$8,672	$8,672	$8,672
Total Cost of Ownership	$266,706	$259,051	$245,025	$248,769	$281,024	$238,026	$242,512	$295,078	$650,780	$295,078	$650,780
Petroleum Use (barrels)	427	336	336	345	20	345	19	2	6	2	6
GHGs (short tons)	242	191	191	206	62	206	62	231	235	231	235
CO (lbs)	337	189	189	346	381	345	379	2,578	2,494	2,578	2,494
NOx (lbs)	553	519	519	560	591	560	588	318	239	278	200
PM10 (lbs)	62	59	59	63	66	63	67	57	57	57	57
PM2.5 (lbs)	20	19	19	21	25	21	25	15	17	15	17
VOC (lbs)	76	68	68	92	155	90	148	92	74	92	74
SOx (lbs)	106	83	83	117	161	114	144	103	79	103	79
Total cost of Externalities	$36,701	$32,060	$32,060	$33,825	$31,492	$33,825	$22,323	$21,354	$20,516	$20,426	$19,589
Total Cost with Externalities	$303,407	$291,111	$277,085	$282,594	$312,516	$271,851	$264,835	$316,432	$671,297	$315,504	$670,369

Note: Values in green represent a cost lower than diesel BAU

Table 18. Summary scenarios for different technologies for class 4 truck - PID 16

Summary scenarios different technologies PID 16 - Class 4	Diesel	Diesel HEV	Diesel HEV HVIP	B20	B100	RD20	RD100	CNG	LNG	CNG Low NOx	LNG Low NOx
Incentive	$0	$0	$15,000	$0	$0	$0	$0	$0	$0	$0	$0
Capital (vehicle+ESVE)	$60,778	$77,609	$63,583	$60,778	$60,778	$60,778	$60,778	$107,773	$247,937	$107,773	$247,937
Fuel	$86,448	$68,069	$68,069	$65,313	$103,319	$52,654	$57,940	$50,450	$81,676	$50,450	$81,676
Diesel Exhaust Fluid	$1,886	$1,485	$1,485	$1,886	$1,886	$1,886	$1,886	$0	$0	$0	$0
Maintenance and Repair	$57,770	$45,411	$45,411	$57,770	$57,770	$57,770	$57,770	$74,131	$261,933	$74,131	$261,933
Insurance	$82,331	$82,331	$82,331	$82,331	$82,331	$82,331	$82,331	$82,331	$82,331	$82,331	$82,331
License and Registration	$8,672	$8,672	$8,672	$8,672	$8,672	$8,672	$8,672	$8,672	$8,672	$8,672	$8,672
Total Cost of Ownership	$297,884	$283,577	$269,551	$276,749	$314,755	$264,091	$269,376	$323,356	$682,548	$323,356	$682,548
Petroleum Use (barrels)	503	396	396	407	23	407	22	3	7	3	7
GHGs (short tons)	285	225	225	243	73	243	73	272	277	272	277
CO (lbs)	468	258	258	479	520	478	518	3,672	3,574	3,672	3,574
NOx (lbs)	756	716	716	765	801	765	798	390	297	333	241
PM10 (lbs)	86	84	84	87	92	88	93	80	81	80	81
PM2.5 (lbs)	27	25	25	28	32	28	33	21	24	21	24
VOC (lbs)	99	90	90	118	192	116	184	116	94	116	94
SOx (lbs)	125	98	98	138	189	134	170	122	93	122	93
Total cost of Externalities	$47,222	$41,754	$41,754	$43,834	$43,565	$43,834	$30,281	$26,972	$25,985	$25,631	$24,644
Total Cost with Externalities	$345,107	$325,331	$311,306	$320,583	$358,320	$307,925	$299,657	$350,328	$708,533	$348,987	$707,193

Note: Values in green represent a cost lower than diesel BAU

Figure 25. TCO for class 5 EV - AFLEET

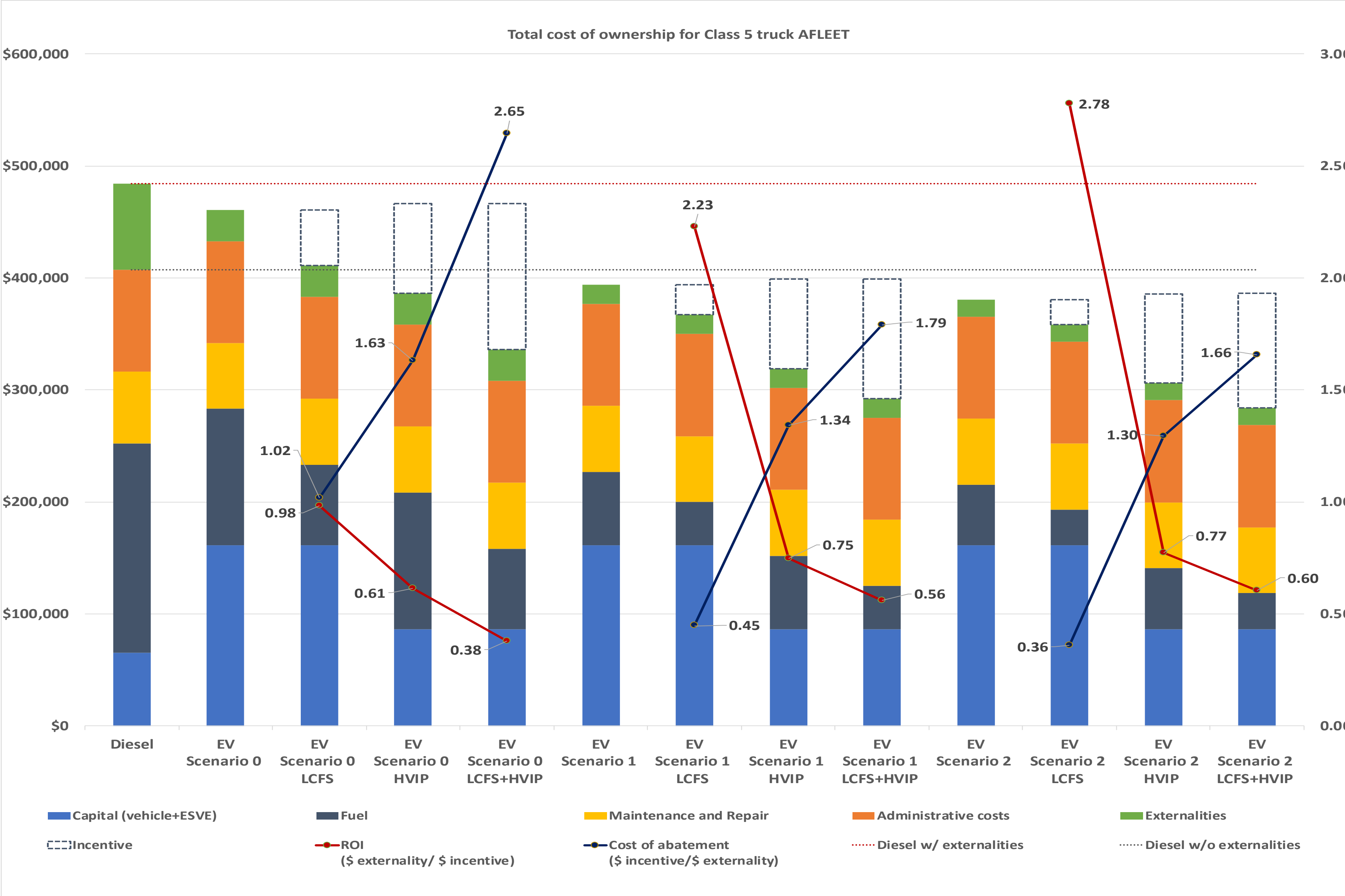


Figure 26. TCO for class 5 – PID 3

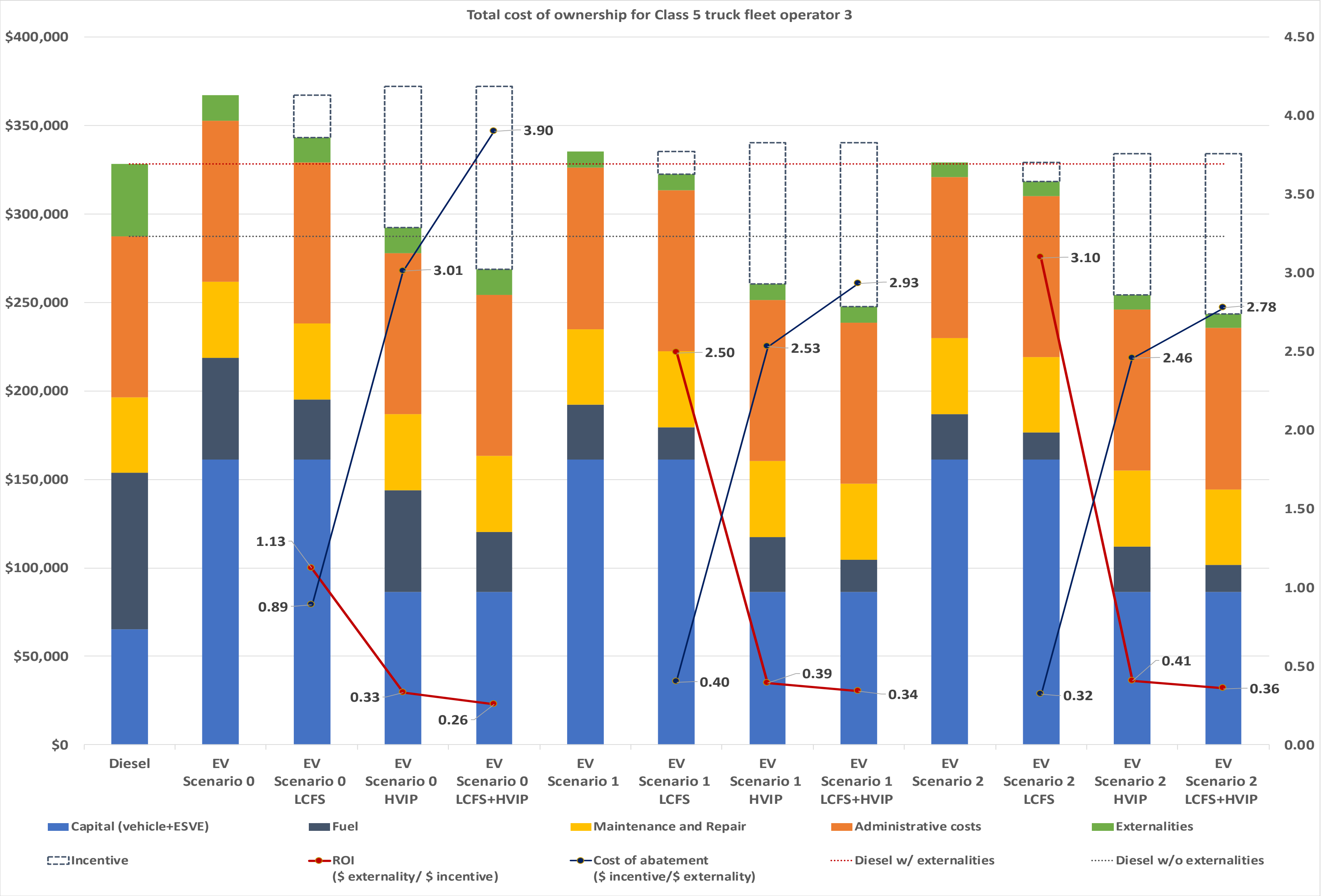
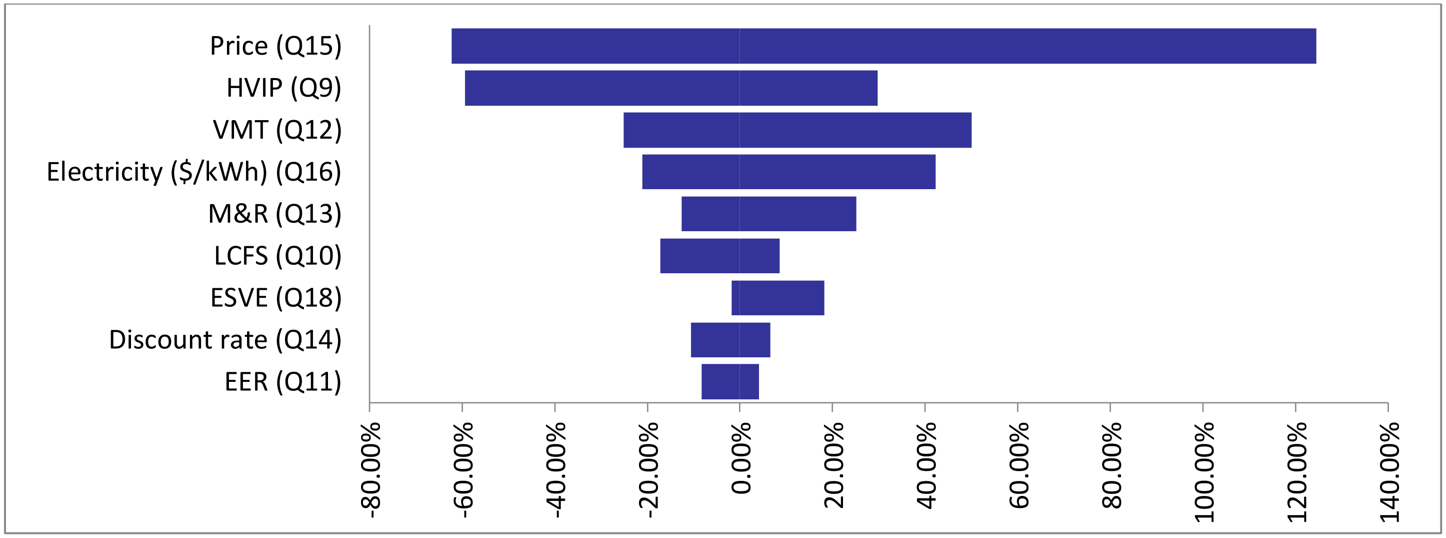


Figure 27. Percent change in TCO class 5 EV – PID 3



Note: All parameters vary from -100% to 200%, except for ESVE that goes from -100% to 10,000%

Table 19. Summary scenarios for different technologies for class 5 truck - AFLEET

Summary scenarios different technologies AFLEET - Class 5	Diesel	Diesel HEV	Diesel HEV HVIP	B20	B100	RD20	RD100	CNG	LNG	CNG Low NOx	LNG Low NOx
Incentive	$0	$0	$15,000	$0	$0	$0	$0	$0	$0	$0	$0
Capital (vehicle+ESVE)	$65,453	$92,569	$78,544	$65,453	$65,453	$65,453	$65,453	$117,099	$253,487	$117,099	$253,487
Fuel	$182,683	$140,710	$140,710	$138,019	$218,334	$111,270	$122,439	$103,742	$167,954	$103,742	$167,954
Diesel Exhaust Fluid	$3,986	$3,070	$3,070	$3,986	$3,986	$3,986	$3,986	$0	$0	$0	$0
Maintenance and Repair	$64,223	$54,233	$54,233	$64,223	$64,223	$64,223	$64,223	$87,665	$270,724	$87,665	$270,724
Insurance	$82,331	$82,331	$82,331	$82,331	$82,331	$82,331	$82,331	$82,331	$82,331	$82,331	$82,331
License and Registration	$8,672	$8,672	$8,672	$8,672	$8,672	$8,672	$8,672	$8,672	$8,672	$8,672	$8,672
Total Cost of Ownership	$407,347	$381,585	$367,559	$362,684	$442,999	$335,934	$347,104	$399,508	$783,168	$399,508	$783,168
Petroleum Use (barrels)	1,063	819	819	860	49	860	47	6	13	6	13
GHGs (short tons)	603	464	464	513	153	513	155	560	570	560	570
CO (lbs)	553	324	324	575	662	574	657	3,846	3,644	3,846	3,644
NOx (lbs)	967	876	876	986	1,062	985	1,056	712	522	655	465
PM10 (lbs)	115	109	109	118	127	118	128	103	104	103	104
PM2.5 (lbs)	42	37	37	44	52	44	54	29	34	29	34
VOC (lbs)	150	128	128	190	346	186	330	192	148	192	148
SOx (lbs)	264	203	203	291	400	283	359	250	192	250	192
Total cost of Externalities	$77,098	$64,611	$64,611	$69,939	$54,449	$69,938	$41,298	$46,316	$44,287	$44,975	$42,946
Total Cost with Externalities	$484,446	$446,196	$432,170	$432,623	$497,447	$405,872	$388,401	$445,825	$827,455	$444,483	$826,114

Note: Values in green represent a cost lower than diesel BAU

Table 20. Summary scenarios for different technologies for class 5 truck - PID 3

Summary scenarios different technologies PID 3 - Class 5	Diesel	Diesel HEV	Diesel HEV HVIP	B20	B100	RD20	RD100	CNG	LNG	CNG Low NOx	LNG Low NOx
Incentive	$0	$0	$15,000	$0	$0	$0	$0	$0	$0	$0	$0
Capital (vehicle+ESVE)	$65,453	$92,569	$78,544	$65,453	$65,453	$65,453	$65,453	$114,049	$252,927	$114,049	$252,927
Fuel	$86,448	$93,318	$93,318	$91,533	$144,797	$73,793	$81,200	$68,801	$111,386	$68,801	$111,386
Diesel Exhaust Fluid	$1,886	$2,036	$2,036	$2,643	$2,643	$2,643	$2,643	$0	$0	$0	$0
Maintenance and Repair	$42,592	$35,967	$35,967	$42,592	$42,592	$42,592	$42,592	$60,334	$246,521	$60,334	$246,521
Insurance	$82,331	$82,331	$82,331	$82,331	$82,331	$82,331	$82,331	$82,331	$82,331	$82,331	$82,331
License and Registration	$8,672	$8,672	$8,672	$8,672	$8,672	$8,672	$8,672	$8,672	$8,672	$8,672	$8,672
Total Cost of Ownership	$287,381	$314,892	$300,867	$293,224	$346,488	$275,484	$282,891	$334,187	$701,837	$334,187	$701,837
Petroleum Use (barrels)	503	543	543	570	32	570	31	4	9	4	9
GHGs (short tons)	285	308	308	340	102	340	103	372	378	372	378
CO (lbs)	333	215	215	381	439	380	436	2,551	2,417	2,551	2,417
NOx (lbs)	566	581	581	654	704	653	700	472	346	435	308
PM10 (lbs)	72	73	73	78	84	78	85	68	69	68	69
PM2.5 (lbs)	23	24	24	29	34	29	36	19	22	19	22
VOC (lbs)	81	85	85	126	230	124	219	128	98	128	98
SOx (lbs)	125	135	135	193	265	187	238	166	127	166	127
Total cost of Externalities	$40,806	$42,849	$42,849	$46,383	$36,110	$46,382	$27,388	$30,716	$29,371	$29,827	$28,481
Total Cost with Externalities	$328,187	$357,742	$343,716	$339,607	$382,598	$321,866	$310,280	$364,904	$731,208	$364,014	$730,318

Note: Values in green represent a cost lower than diesel BAU

Figure 28. TCO for class 6 EV - AFLEET

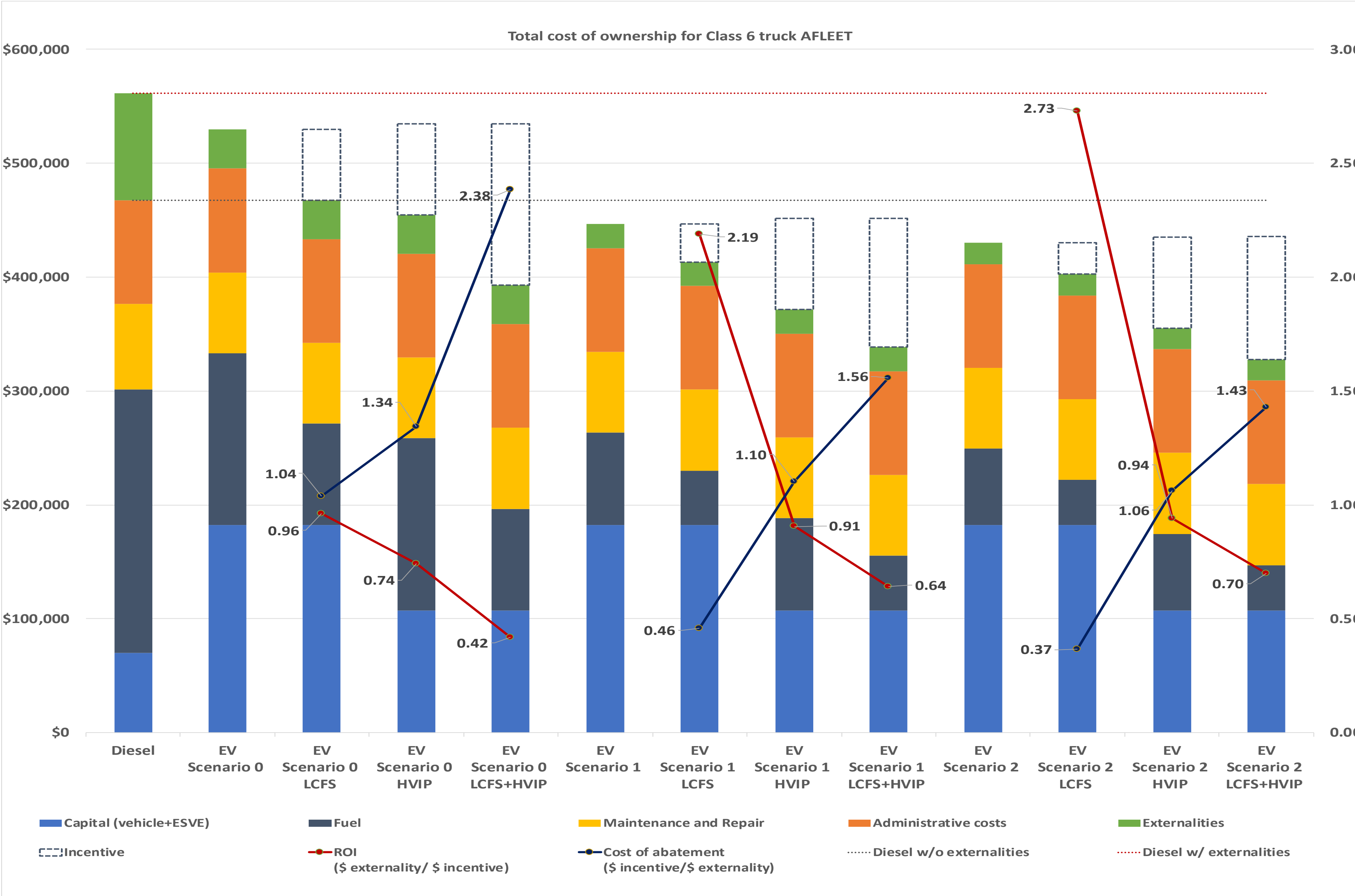


Figure 29. TCO for class 6 EV – PID 16

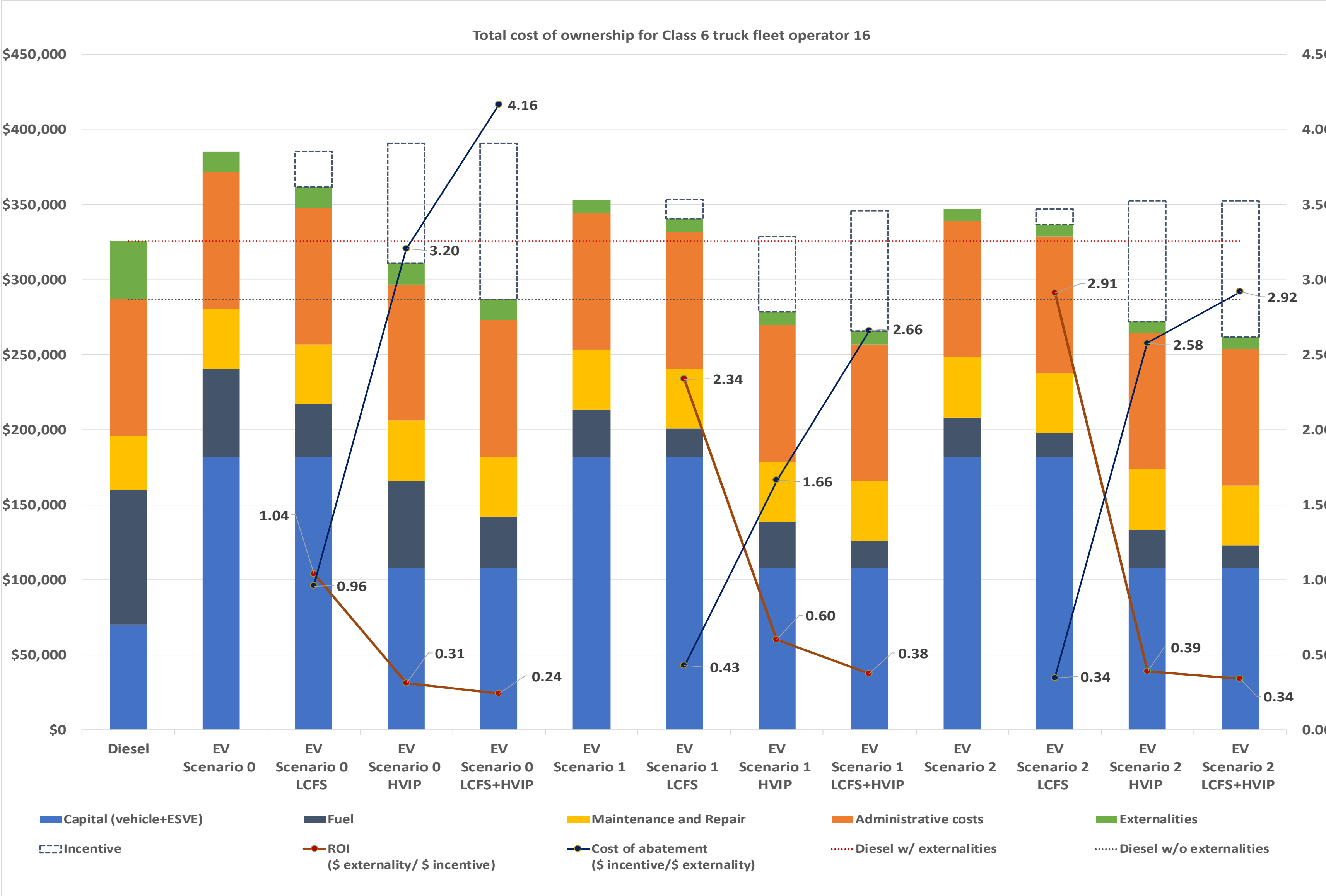
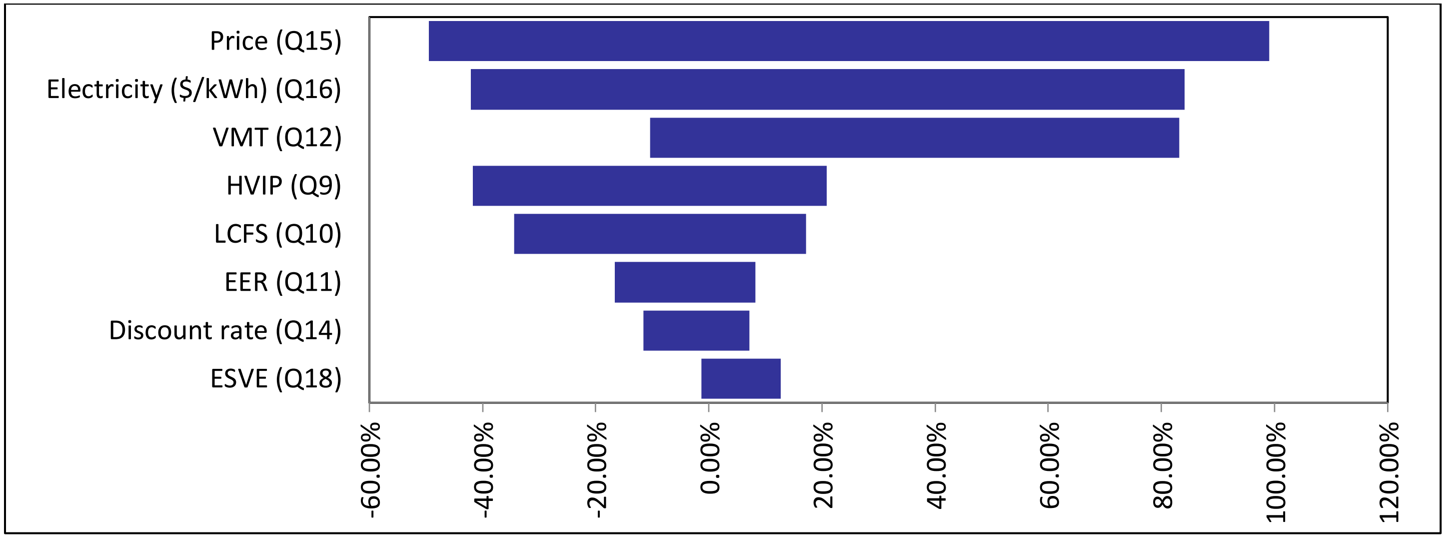


Figure 30. Percent change for TCO class 6 EV – PID 16



Note: All parameters vary from -100% to 200%, except for ESVE that goes from -100% to 10,000%

Table 21. Summary scenarios for different technologies for class 6 truck - AFLEET

Summary scenarios different technologies AFLEET - Class 6	Diesel	Diesel HEV	Diesel HEV HVIP	B20	B100	RD20	RD100	CNG	LNG	CNG Low NOx	LNG Low NOx
Incentive	$0	$0	$15,000	$0	$0	$0	$0	$0	$0	$0	$0
Capital (vehicle+ESVE)	$70,128	$107,530	$93,504	$70,128	$70,128	$70,128	$70,128	$123,604	$258,558	$123,604	$258,558
Fuel	$226,283	$170,114	$170,114	$170,960	$270,443	$137,826	$151,661	$124,719	$201,915	$124,719	$201,915
Diesel Exhaust Fluid	$4,937	$3,711	$3,711	$4,937	$4,937	$4,937	$4,937	$0	$0	$0	$0
Maintenance and Repair	$75,346	$67,959	$67,959	$75,346	$75,346	$75,346	$75,346	$102,923	$284,181	$102,923	$284,181
Insurance	$82,331	$82,331	$82,331	$82,331	$82,331	$82,331	$82,331	$82,331	$82,331	$82,331	$82,331
License and Registration	$8,672	$8,672	$8,672	$8,672	$8,672	$8,672	$8,672	$8,672	$8,672	$8,672	$8,672
Total Cost of Ownership	$467,696	$440,317	$426,291	$412,373	$511,856	$379,239	$393,074	$442,249	$835,657	$442,249	$835,657
Petroleum Use (barrels)	1,317	990	990	1,065	60	1,065	59	7	16	7	16
GHGs (short tons)	747	561	561	635	190	636	192	674	685	674	685
CO (lbs)	657	384	384	684	792	683	786	4,498	4,255	4,498	4,255
NOx (lbs)	1,156	1,033	1,033	1,179	1,273	1,178	1,266	853	624	787	558
PM10 (lbs)	136	128	128	139	151	140	153	120	122	120	122
PM2.5 (lbs)	50	43	43	52	63	53	66	34	40	34	40
VOC (lbs)	182	152	152	231	425	227	404	230	177	230	177
SOx (lbs)	327	246	246	360	495	350	444	301	231	301	231
Total cost of Externalities	$93,813	$77,103	$77,103	$84,945	$64,764	$84,944	$49,468	$55,268	$52,828	$53,706	$51,266
Total Cost with Externalities	$561,509	$517,419	$503,394	$497,318	$576,620	$464,183	$442,543	$497,517	$888,485	$495,956	$886,923

Note: Values in green represent a cost lower than diesel BAU

Table 22. Summary scenarios for different technologies for class 6 truck - PID 16

Summary scenarios different technologies PID 16 - Class 6	Diesel	Diesel HEV	Diesel HEV HVIP	B20	B100	RD20	RD100	CNG	LNG	CNG Low NOx	LNG Low NOx
Incentive	$0	$0	$15,000	$0	$0	$0	$0	$0	$0	$0	$0
Capital (vehicle+ESVE)	$70,128	$107,530	$93,504	$70,128	$70,128	$70,128	$70,128	$116,941	$257,299	$116,941	$257,299
Fuel	$87,740	$45,204	$45,204	$66,289	$104,863	$53,441	$58,806	$48,359	$78,291	$48,359	$78,291
Diesel Exhaust Fluid	$1,914	$986	$986	$1,914	$1,914	$1,914	$1,914	$0	$0	$0	$0
Maintenance and Repair	$36,178	$32,631	$32,631	$36,178	$36,178	$36,178	$36,178	$51,545	$239,591	$51,545	$239,591
Insurance	$82,331	$82,331	$82,331	$82,331	$82,331	$82,331	$82,331	$82,331	$82,331	$82,331	$82,331
License and Registration	$8,672	$8,672	$8,672	$8,672	$8,672	$8,672	$8,672	$8,672	$8,672	$8,672	$8,672
Total Cost of Ownership	$286,963	$277,354	$263,328	$265,511	$304,085	$252,664	$258,028	$307,847	$666,184	$307,847	$666,184
Petroleum Use (barrels)	511	263	263	413	23	413	23	3	6	3	6
GHGs (short tons)	290	149	149	246	74	247	74	261	265	261	265
CO (lbs)	295	149	149	306	347	305	345	2,105	2,011	2,105	2,011
NOx (lbs)	509	417	417	518	555	518	552	340	251	308	219
PM10 (lbs)	62	56	56	64	68	64	69	56	57	56	57
PM2.5 (lbs)	22	17	17	23	26	23	28	15	18	15	18
VOC (lbs)	76	54	54	95	171	94	162	93	73	93	73
SOx (lbs)	127	65	65	140	192	136	172	117	89	117	89
Total cost of Externalities	$38,824	$26,169	$26,169	$35,385	$29,004	$35,385	$21,629	$22,612	$21,666	$21,862	$20,916
Total Cost with Externalities	$325,786	$303,523	$289,498	$300,896	$333,089	$288,049	$279,658	$330,459	$687,849	$329,709	$687,099

Note: Values in green represent a cost lower than diesel BAU

Figure 31. TCO for class 7 EV - AFLEET

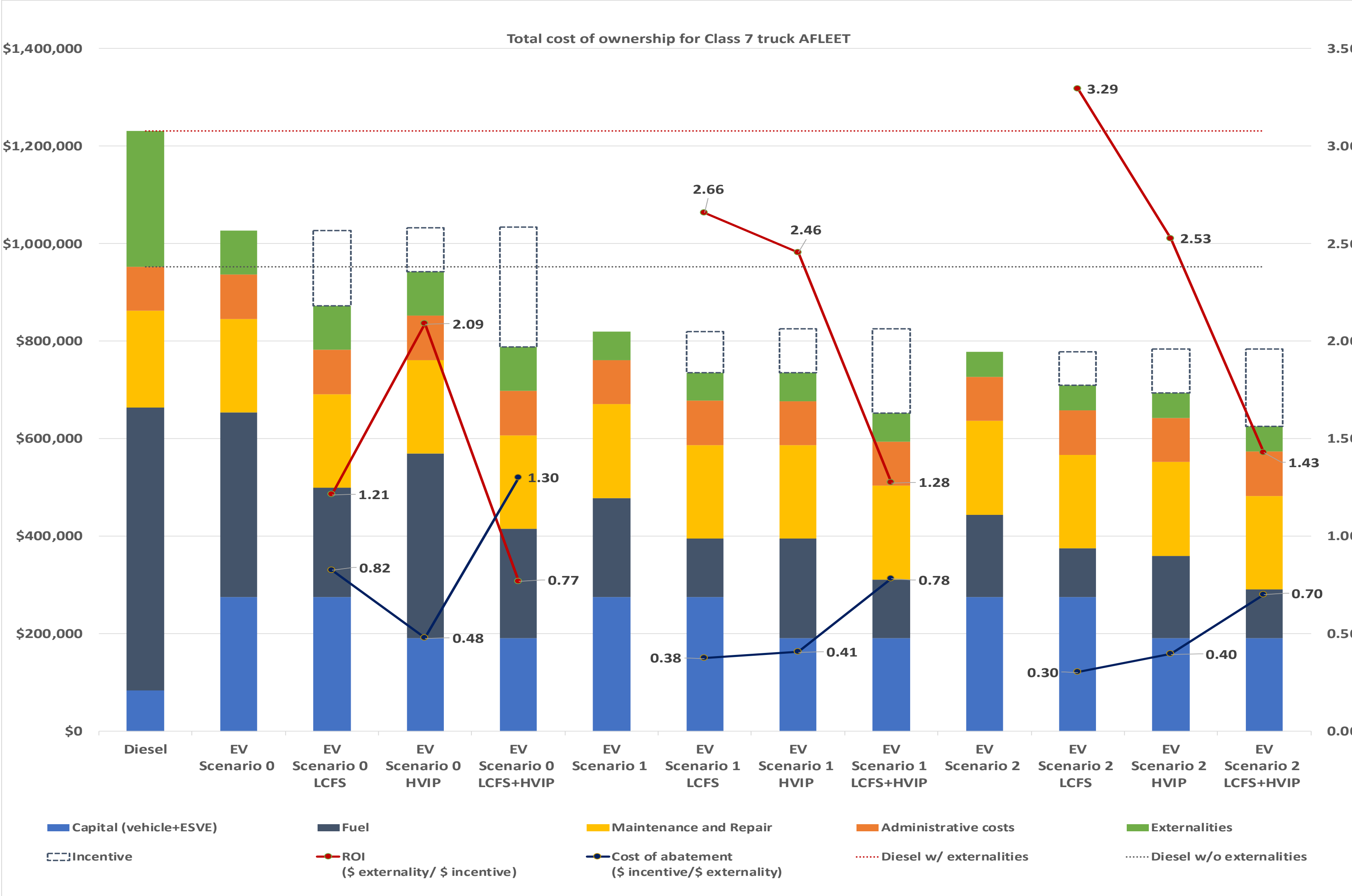


Figure 32. TCO for class 7 EV – PID 3

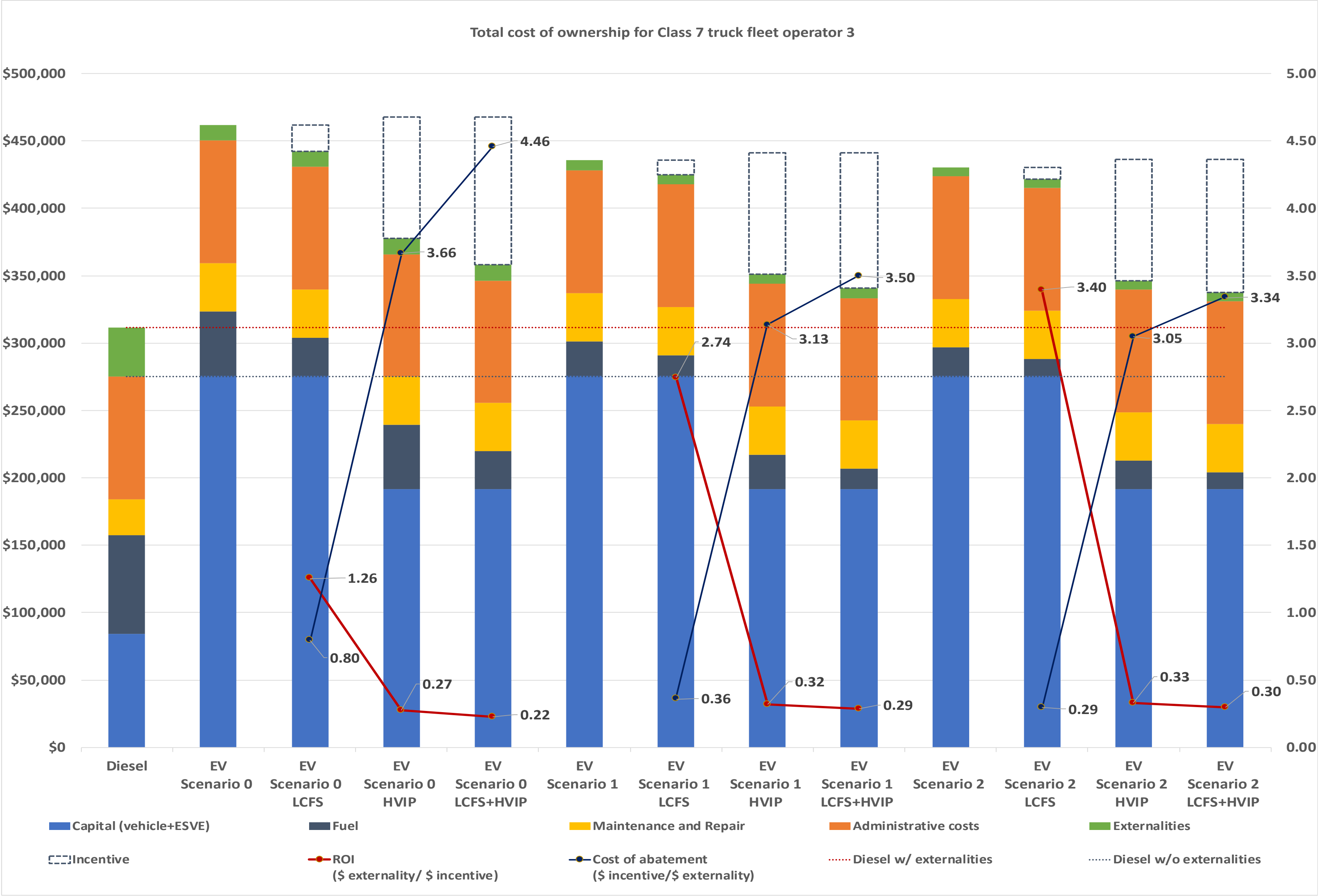
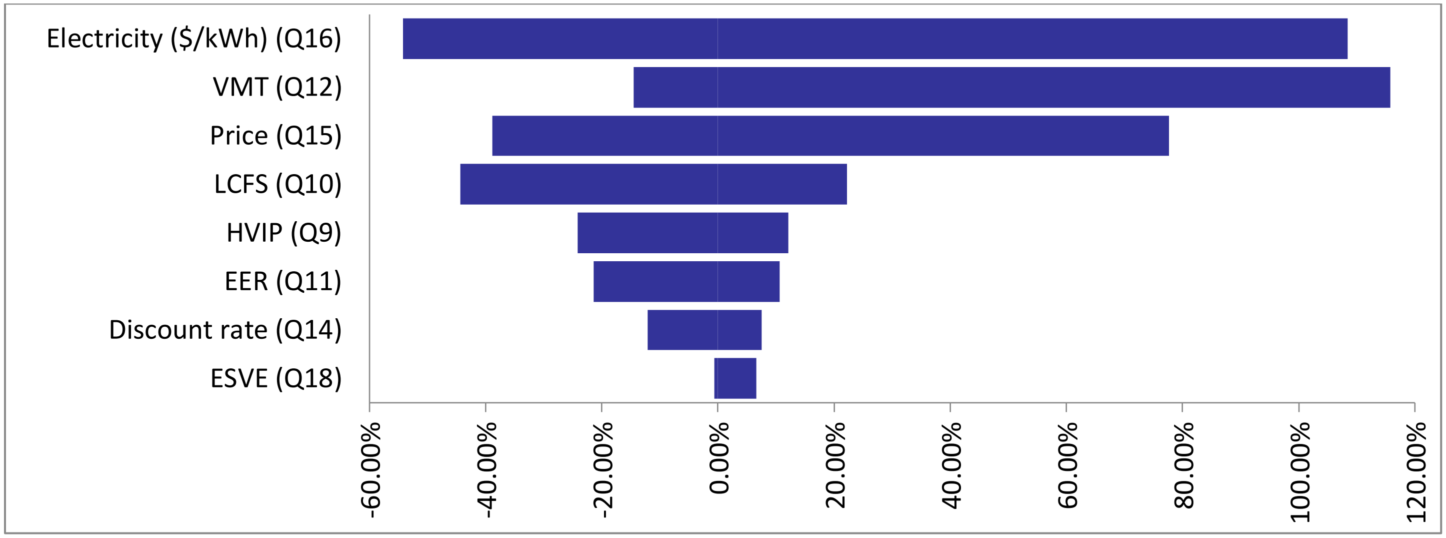


Figure 33. Percent change in TCO for class 7 EV – PID 3



Note: All parameters vary from -100% to 200%, except for ESVE that goes from -100% to 10,000%

Table 23. Summary scenarios for different technologies for class 7 truck - AFLEET

Summary scenarios different technologies AFLEET - Class 7	Diesel	Diesel HEV	Diesel HEV HVIP	B20	B100	RD20	RD100	CNG	LNG	CNG Low NOx	LNG Low NOx
Incentive											
Capital (vehicle+ESVE)	$84,154	$128,568	$128,568	$84,154	$84,154	$84,154	$84,154	$154,033	$270,527	$154,033	$270,527
Fuel	$567,294	$533,256	$533,256	$428,598	$678,004	$345,531	$380,216	$312,672	$506,202	$312,672	$506,202
Diesel Exhaust Fluid	$12,377	$11,634	$11,634	$12,377	$12,377	$12,377	$12,377	$0	$0	$0	$0
Maintenance and Repair	$198,320	$188,926	$188,926	$198,320	$198,320	$198,320	$198,320	$242,362	$400,432	$242,362	$400,432
Insurance	$82,331	$82,331	$82,331	$82,331	$82,331	$82,331	$82,331	$82,331	$82,331	$82,331	$82,331
License and Registration	$8,672	$8,672	$8,672	$8,672	$8,672	$8,672	$8,672	$8,672	$8,672	$8,672	$8,672
Total Cost of Ownership	$953,147	$953,388	$953,388	$814,451	$1,063,857	$731,384	$766,070	$800,069	$1,268,164	$800,069	$1,268,164
Petroleum Use (barrels)	3,301	3,103	3,103	2,671	151	2,670	147	17	41	17	41
GHGs (short tons)	1,872	1,760	1,760	1,593	476	1,594	481	1,689	1,716	1,689	1,716
CO (lbs)	1,735	1,109	1,109	1,802	2,073	1,800	2,059	19,493	18,884	19,493	18,884
NOx (lbs)	4,163	4,089	4,089	4,222	4,456	4,218	4,438	2,328	1,754	2,036	1,461
PM10 (lbs)	447	443	443	455	483	456	488	406	411	406	411
PM2.5 (lbs)	160	156	156	166	192	168	199	120	134	120	134
VOC (lbs)	515	496	496	636	1,123	626	1,071	572	439	572	439
SOx (lbs)	819	770	770	903	1,242	878	1,114	754	579	754	579
Total cost of Externalities	$278,539	$268,413	$268,413	$256,307	$235,377	$256,304	$167,366	$155,109	$148,993	$148,227	$142,111
Total Cost with Externalities	$1,231,686	$1,221,800	$1,221,800	$1,070,758	$1,299,234	$987,689	$933,436	$955,178	$1,417,157	$948,296	$1,410,275

Note: Values in green represent a cost lower than diesel BAU

Table 24. Summary scenarios for different technologies for class 7 truck - PID 3

Summary scenarios different technologies PID 3 - Class 7	Diesel	Diesel HEV	Diesel HEV HVIP	B20	B100	RD20	RD100	CNG	LNG	CNG Low NOx	LNG Low NOx
Incentive											
Capital (vehicle+ESVE)	$84,154	$128,568	$114,543	$84,154	$84,154	$84,154	$84,154	$130,185	$270,527	$130,185	$270,527
Fuel	$71,503	$67,213	$67,213	$54,021	$85,457	$43,551	$47,923	$39,410	$63,803	$39,410	$63,803
Diesel Exhaust Fluid	$1,560	$1,466	$1,466	$1,560	$1,560	$1,560	$1,560	$0	$0	$0	$0
Maintenance and Repair	$26,876	$25,603	$25,603	$26,876	$26,876	$26,876	$26,876	$38,156	$226,181	$38,156	$226,181
Insurance	$82,331	$82,331	$82,331	$82,331	$82,331	$82,331	$82,331	$82,331	$82,331	$82,331	$82,331
License and Registration	$8,672	$8,672	$8,672	$8,672	$8,672	$8,672	$8,672	$8,672	$8,672	$8,672	$8,672
Total Cost of Ownership	$275,095	$313,853	$299,827	$257,614	$289,049	$247,144	$251,516	$298,753	$651,513	$298,753	$651,513
Petroleum Use (barrels)	416	391	391	337	19	337	19	2	5	2	5
GHGs (short tons)	236	222	222	201	60	201	61	213	216	213	216
CO (lbs)	230	145	145	238	273	238	271	2,628	2,551	2,628	2,551
NOx (lbs)	552	543	543	560	589	559	587	298	225	258	186
PM10 (lbs)	60	59	59	61	64	61	65	55	55	55	55
PM2.5 (lbs)	21	21	21	22	25	22	26	16	18	16	18
VOC (lbs)	67	65	65	82	144	81	137	73	56	73	56
SOx (lbs)	103	97	97	114	157	111	140	95	73	95	73
Total cost of Externalities	$36,148	$34,871	$34,871	$33,346	$31,360	$33,345	$22,135	$20,011	$19,240	$19,078	$18,307
Total Cost with Externalities	$311,243	$348,724	$334,699	$290,959	$320,409	$280,489	$273,651	$318,764	$670,753	$317,831	$669,820

Note: Values in green represent a cost lower than diesel BAU