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Quantitative Evaluation of MD/HD Vehicle Electrification Using Statistical Data

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ABSTRACT

This paper presents a wide-ranging analysis of Class 3-8 commercial vehicle electrification by means of developing a framework tool which uses a quantitative method of estimating electric vehicle energy consumption and appropriate charging considerations. The Fleet DNA composite statistics on real world driving behavior is used to evaluate feasible or market-ready battery electric vehicle (BEV) technologies in medium- and heavy-duty (MD/HD) applications. In the paper, ten representative Class 3-8 commercial vehicle electrifications have been evaluated as a function of various service coverages, including applications in port drayage tractors, refuse trucks, delivery trucks, buses, and bucket trucks. The results indicate significant energy savings and fuel cost savings across all MD/HD vehicle electrifications. The majority of MD BEVs, with the exception of Class 3 bucket trucks, achieve better than a 5-year payback with 50-75% service coverage. For HD BEVs, with the exception of the Class 8 port drayage tractors, the 90% service coverage results in a 10-year or longer payback time, while the 50% service coverage yields a 7-8 year payback. Class 8 port drayage tractors should achieve payback in no more than a 3.5 years with 50-75% service coverage. Thus, the analysis indicates a highly feasible potential for class 3-6 MD vehicles to be electrified, and feasible opportunities for electrification in class 7-8 HD short-distance applications.

INTRODUCTION

The United States is the world's largest user of oil and refined petroleum products [1]. Much of this demand is contributed by the transportation sector, which has been responsible for about 65% of U.S. carbon dioxide emissions over the last twenty years [2]. Transportation vehicle electrification offers substantial benefits for local air quality, greenhouse gas emissions, and petroleum use [3]. Electrification is particularly vital for medium-duty (MD) and heavy-duty (HD) vehicles which account for nearly 20% of the nation's transportation fuel consumption [4]. In fact, battery electric vehicle (BEV) technology is preferably suited for many MD and HD applications with well-defined routes, frequent stops, long idle times, and lower average speeds. Many U.S. nationwide fleets have shown significant interest and made commitments to electrify part of their fleet, even with significant cost penalties, in order to benefit the community, environment, and economy [5-6]. Significant growth is expected in the future MD and HD electric vehicle market [7].

However, compared to light-duty (LD) BEVs, there are few MD and HD BEVs on the road to date. This is in part because not all LD BEV technologies can be transferred directly to MD and HD applications due to requirements for higher power and the durability to withstand harsh working environments [8]. Moreover, the MD and HD vehicle market covers a wide diversity of commercial vocations, operational patterns, and duty cycles [3]. Table 1 summarizes the existing MD/HD vehicle electrification technologies and readiness. Due to differences in duty cycles, one truck electrification model cannot fit many diverse truck applications. As a result, MD and HD vehicle electrification options are still in limited commercial availability, although electrification technologies have been widely applied to transit buses, school buses, MD and HD trucks. At present, five manufacturers offer commercial battery electric transit buses for sale in the US, including Proterra, BYD, New Flyer, GreenPower, and Nova [8]. These commercial transit electric buses are being tested in New York [9], Chicago [10], St. Louis [11], California [12] etc. Like transit buses, school buses operate in urban and suburban environments. Lion, Motiv Power systems, TransPower and Adomani have demonstrated their battery all-electric school bus with 80-400kWh battery [13-16]. California Highway Patrol's electric school bus demonstration projects show the significant potential for fuel cost savings [13-14]. However, the large school bus manufacturers in the U.S., such as Bluebird, IC Bus and Thomas Built, are not involved in electric bus production due to a number of factors, including safety certification [8]. School buses are not yet as commercially available as transit buses.

Class 3-6 MD vehicle electrification could benefit from technology transferred from LD applications to a larger degree than Class 7-8 HD trucks and buses, because MD trucks and vans require less power and drive fewer miles. The electric vehicles in this category are being used in optimal duty cycles such as local delivery and food distribution [15-17]. Several manufacturers produce electric trucks/vans for food/beverage, parcel delivery, utility and maintenance work, and other vocational applications, with gross vehicle weight (GVW) ranging from 10,000 to 26,000 pounds [17]. High profile fleets, such as Frito-Lay, Staples, and Coca-Cola, have made big investments in E-trucks that haul as much as 16,000 pounds, with a range up to 100 miles on a single charge [15]. It is expected that widespread penetration into the market place will occur in the next 5 to 10 years [8]. HD vehicle electrification is currently in the field demonstration phase by the manufacturers including Balqon, BYD, Electric Vehicles International, Motiv Power System, TransPower, ZeroTruck, and others [3, 7]. There are also 12 other Class 8 BEVs in varying stages of prototype manufacture [7], including Cummins and Tesla [18]. The major efforts of truck electrification in Class 8 have been started with vocations that have optimal duty

cycles, like short-haul for drayage operations, local delivery and urban refuse trucks [8, 18]. However, there are not commercial HD battery electric trucks available at the moment due to the large gap of battery cost and fast charging technologies.

MD/HD vehicle electrification is still in very early stages of development, despite high expectations for their future market. Significant research is needed to understand (1) battery electric vehicle feasibility and priority across types and duties (or vocations) of MD/HD vehicles; (2) cost-effectiveness of electrification across types and duties of these commercial vehicles; and (3) the high-potential of MD/HD electrification technologies and market opportunities to align stakeholder needs and policy considerations with qualitative and quantitative analysis planning. An in-depth analysis is particularly essential to identify the challenges and opportunities of MD/HD electrification over a wide range of driving patterns related to MD/HD vocations. Therefore, this study will apply a quantitative method with electric vehicle energy consumption and appropriate charging assumptions to conduct a comprehensive priority analysis of commercial vehicle electrification. A wide range of vehicle types and operations used in the method comes from Fleet DNA statistical data, which are collected by National Renewable Energy Laboratory (NREL), covering a substantial number of day-to-day real routes performed by MD and HD vehicles [19]. To keep the problem tractable, the energy consumption analysis was restricted to use the modified vehicle tractive energy methodology using the statistical drive data and component efficiency for describing vehicle performance. In addition, MD/HD electrification cost-effectiveness is also addressed in the developed tool.

DRIVING DATA, METHODOLOGY AND ASSUMPTION

This section describes drive data, vehicle energy methodology for tractive energy, brake forces, and vehicle component efficiencies, as well as the assumptions for modeling MD/HD conventional and battery electric vehicles.

Driving Data

Fleet DNA data provide a wide range of operation statistics for many of today's Class 3-8 MD and HD vehicles, covering transit buses, school buses, delivery vehicles, regional tractors, utility trucks, refuse trucks, bucket trucks, cabs, sleeper-cab trucks, and many others [19]. The datasets include extensive vehicle driving statistical information, such as aggregated route distance, average speed, stop events per mile, deceleration events per mile, drive duration, stop duration, deceleration duration, load and grade statistics, and many other drive-cycle metrics and travel features. The Fleet DNA data also provide specific operating energy consumption, allowing more customized results to be produced from the Fleet DNA data formation. To keep the current study in reasonable order, ten representative Class 3-8 MD/HD vehicles with optimal driving cycle features were selected in the current electrification analysis. Table 2 summarizes the driving information of these vehicles.

The 10 class 3-8 MD/HD vocations cover a widely distinguished range of driving patterns. Naturally, Class 7-8 vehicles have longer daily travel mileage, and their maximum daily travel mileage is much greater than the average daily travel mileage. Figure 1 displays two examples of the driving statistics (i.e., class 7 food delivery tractors and class 8 port drayage tractors), showing a long-tailed distribution in both the cases. The observation illustrates that the

percentage of aggressive daily travel mileage is actually quite limited. This insight illustrates that it is not necessary for MD/HD electric vehicles to cover all-days service conducted by conventional vehicles in order to achieve cost effectiveness and reasonable battery size.

In addition, the Fleet DNA data also shows the stop or idling events of MD/HD vocations. The stop or idling events with a minimum 5-minute stop typically occurs at the fleet garage, depot or vocation stop sites after completing a major operation or a trip, as are defined as trip count in the Fleet DNA database. The trip count per day can actually be considered as the opportunities of BEVs' daily en-route charging, and is discussed later in this paper.

Vehicle Energy Methodology

An equation of typical tractive power demand is used to account for vehicle forward acceleration, rotational inertia, aerodynamic loss, rolling resistance loss, and road grade. For any instant of time, the tractive power demand is described as [20-22]:

$$W_{tract} = m \cdot V \cdot dV/dt + \frac{1}{2}\rho \cdot C_d \cdot A_f \cdot V^3 + m \cdot g \cdot C_{rr} \cdot V + m \cdot g \cdot V \cdot \sin(\theta) \quad (1)$$

where W_{tract} is vehicle tractive power; V is velocity; ρ is air density; C_d is the aerodynamic drag coefficient; A_f is the projected frontal area; C_{rr} is the rolling resistance coefficient; θ is road gradient; g is gravity; t is time; m is gross vehicle weight, including passengers and key components for powertrain and drivetrain systems (e.g., engine, clutch/torque converter, gearbox, final drive, wheel, chassis, generator, battery, mechanical and electrical accessory, as well as motor and high-voltage battery for hybrid powertrain).

For a conventional vehicle, the tractive power is positive if the vehicle is being actively propelled; and the tractive power becomes negative during braking. Braking represents a dissipative force that depletes the energy that is stored as vehicle kinetic and potential energy. According to Fleet DNA data, a vehicle propels energy over a daily operating time of ΔT, estimated in the modified equation listed below:

$$E_{prop} = \int_{\Delta T} \left[m \cdot V \cdot dV/dt + \frac{1}{2}\rho \cdot C_d \cdot A_f \cdot V^3 + m \cdot g \cdot C_{rr} \cdot V + m \cdot g \cdot V \cdot sin(\theta) \right] dt + E_{brk} \quad (2a)$$

Then the equation is further formatted as:

$$E_{prop} = \left[m \cdot (\bar{E}_k(a > 0) + \bar{E}_k(a < 0)) + \rho \cdot C_d \cdot A_f \cdot \bar{E}_{Cd} + m \cdot C_{rr} \cdot \bar{E}_{Crr} + m \cdot (\bar{E}_p(\theta > 0) + \bar{E}_p(\theta < 0)) \right] \cdot \Delta T + E_{brk} \quad (2b)$$

where a represents acceleration; $\bar{E}_k(\mathrm{a} > 0)$ and $\bar{E}_k(\mathrm{a} < 0)$ are averaged specific positive/negative kinetic energy in unit of kJ/kg; $\bar{E}_{Cd}$ is averaged specific aerodynamic energy in unit of kJ-m/kg; $\bar{E}_{Crr}$ is averaged specific rolling resistance energy in unit of kW/kg; $\bar{E}_p(\theta > 0)$ are $\bar{E}_p(\theta < 0)$ are averaged specific positive/negative potential energy in units of kW/kg, respectively. All these statistical energy terms are provided by the Fleet DNA database. E_{brk} represents braking energy loss for all vehicle deceleration events, which is used for compensating the negative tractive energy encompassed in the derived propel energy shown in the first term at the right side of Eqs. 2(a) and 2(b). E_{brk} is evaluated based on the statistical data (i.e. $\bar{V}_{drive}$: average drive speed; δ_{decel}: average deceleration event duration; n_{decel}: deceleration events per mile; and d_{dist}: driving distance) with the assumption of a linear deceleration stop of $V = \alpha_{decel} \cdot t$, where $\alpha_{decel} = \bar{V}_{drive} / \delta_{decel}$, then it is derived from Eq. 1 without considering elevation changes:

$$E_{brk} = \left(\frac{1}{2} m \cdot a_{decel}^2 \cdot \delta_{decel}^2 + \frac{1}{8}\rho \cdot C_d \cdot A_f \cdot a_{decel}^3 \cdot \delta_{decel}^4 + \frac{1}{2} m \cdot g \cdot C_{rr} \cdot a_{decel} \cdot \delta_{decel}^2 \right) \cdot n_{decel} \cdot d_{dist} \quad (3)$$

When a conventional vehicle is being actively propelled, the vehicle engine provides power to the wheels. Tractive power becomes zero when the vehicle is at idling or braking, but the engine still has to run to satisfy accessory loads. Thus, mechanical power output from the engine is derived from drivetrain component efficiencies, as described below.

$$E_{eng}^{c} = E_{acc}^{c} + E_{prop}^{c}/\eta_{wh} \cdot \eta_{fd} \cdot \eta_{gb} \cdot \eta_{cl} \tag{4a}$$

$$E_{fuel}^{c} = E_{eng}^{c}/\eta_{eng} \tag{4b}$$

where η_{wh} is wheel efficiency; η_{fd} is final drive efficiency; η_{gb} is gearbox efficiency; η_{cl} is clutch efficiency; E_{acc}^{c} is overall energy for accessory load of a conventional vehicle, simply expressed as $\int_{\Delta T} W_{acc}^{c}\, dt$, and W_{acc}^{c} is considered as constant value; the superscript *c* represents conventional vehicle.

In an electric vehicle, electric power output from the battery is derived based on the efficiencies of electric components (i.e. motor and battery) and related drivetrain components (e.g. final drive and wheel), shown in Eq. (5). However, an electric vehicle is capable of converting vehicle kinetic energy into a storable form of battery energy during braking if satisfying the thresholds of vehicle speed and acceleration. The current electric vehicle model assumes braking energy regeneration is allowed to occur once vehicle speed is not below the given value (i.e. v_{lb}), as is described as Eq. 6; otherwise, braking energy regeneration does not occur in order to avoid a kinetic energy regeneration that is too low. The battery electrical energy consumption is described as:

$$E_{batt}^{e} = E_{acc}^{e} + E_{prop}^{e}/\eta_{wh} \cdot \eta_{fd} \cdot \eta_{mot} \cdot \eta_{batt} - E_{regen}^{e} \tag{5}$$

where η_{mot} is motor efficiency; η_{batt} is battery efficiency; η_{chgr} is charger efficiency; E_{acc}^{e} is overall energy for electric accessory load, simply expressed in $\int_{\Delta T} W_{acc}^{e}\, dt$, where W_{acc}^{e} is considered as constant value; the superscript *e* represents electric vehicle. E_{regen}^{e} is potential electrical energy generated from braking energy regeneration, estimated as below:

$$E_{regen}^{e} = \left(E_{brk} - E_{brk,lb} \right)/\eta_{wh} \cdot \eta_{fd} \cdot \eta_{mot} \cdot \eta_{batt} \tag{6a}$$

$$E_{brk_lb} = \left(\frac{1}{2} m \cdot V_{lb}^{2} + \frac{1}{8} \rho \cdot C_{d} \cdot A_{f} \cdot V_{lb}^{3} \cdot \delta_{lb} + \frac{1}{2} m \cdot g \cdot C_{rr} \cdot V_{lb} \cdot \delta_{lb} \right) \cdot n_{decel} \cdot d_{dist} \tag{6b}$$

where V_{lb} is the low–boundary for vehicle speed in converting kinetic energy into electric energy; δ_{lb} is deceleration time from low boundary speed to full stop, estimated by $V_{lb} = \alpha_{decel} \cdot \delta_{lb}$; E_{brk_lb} represents braking energy loss due to too low vehicle speed in recovering kinetic energy during vehicle deceleration events.

Unlike for conventional vehicles, it is important for electric vehicle drivers to deliberate en-route charging activities. To simplify the process, trip count per day, n_{trip}, in Fleet DNA is considered as EV en-route charging slots for each service day. However, the charging process should be limited by charger power level, battery capacity and battery energy consumption, shown in Eq. 7. In the simulations, different charging power levels and times are required.

$$E_{chg}^{e} = \min\left(E_{batt}^{e}/n_{trip}, \eta_{chgr} \cdot \int_{\delta_{chg}} W_{chgr}^{e} dt, (1 - SOC_{lb}) \cdot C_{batt} \right) \tag{7}$$

where η_{chgr} is charger efficiency, which is considered to be constant; W_{chgr}^{e} is charging power; δ_{chg} is charging time; SOC_{lb} is the low-boundary SOC for safety and battery protection, which is assumed to be 10%; C_{batt} is battery capacity.

Also, an EV battery typically leads to a significant weight penalty due to low battery energy density. Thus, the BEV weight penalty is considered in the GVW of the above tractive energy equations, and given as:

$$m_{extra} = m_{batt} + m_{mot} + m_{cov/inv} - m_{eng} - m_{cpl} - m_{gb} - m_{cat} \quad (8)$$

where m_{batt}, m_{mot}, $m_{cov/inv}$, m_{eng}, m_{cpl}, m_{gb} and m_{cat} are the weight of battery, motor, converter/inverter, engine, clutch, gearbox and aftertreatment system, respectively. These component weights are estimated based on their peak powers except battery. Battery weight is determined based on battery capacity. The detailed mass estimations have been addressed in our previous works [22].

Vehicle and Charging Assumptions

The studied ten conventional MD/HD vehicle configurations were constructed based on an ORNL database and open literatures. The considered components include engine, clutch, gearbox, final drive, wheel and chassis. Table 3 details these modeled MD/HD applications. The frontal area, rolling resistance, and aerodynamic drag coefficient were estimated based on the ORNL MD/HD vehicle database. Also, appropriate constant average efficiencies for each powertrain and drivetrain components were assumed [22-25]. Constant values for the accessories power consumption were adopted correspondingly. The considered GVWs of the MD/HD vehicles are based on the statistical data provided in FLEET DNA.

To ensure the methodology and assumptions provide reasonable predictions for MD/HD conventional vehicles, a Class 7 transit bus was selected for the validation. We compared the predicted simulations with one-year real driving data recorded by ORNL in three 2005 Optima buses [24]. The results show an overall 4.74 mpg in the current simulation vs. 4.38 mpg of the measurement, indicating an 8% over-predicted error, implying the modified methodology and assumptions for conventional vehicles achieve a reasonable accuracy.

For electric vehicles, the major components considered are battery, motor, final drive, wheel and chassis. Similarly constant average efficiencies for motor and battery components were assumed [3, 22]. Table 3 lists the electric component features. Other drivetrain components and chassis parameters are considered as the same as those used in the conventional vehicle. Similarly, a constant value of accessory load is considered in the modeled electric vehicle, but the accessory load in the electric vehicles is assumed 50% less than a conventional vehicle. The identical assumption has been widely used in open literature due to lower accessory energy consumption in EV [22-25]. The BEV mass weight is estimated based on the comparable conventional vehicle weight plus BEV mass penalty predicted using Eq. 8.

Due to very limited MD/HD electric vehicle data available, it is difficult to calibrate the EV model directly. Thus, we utilized our previous well-calibrated electric bus model based on the same 2005 Optima bus, as well as ORNL second-by-second driving data, to validate the current BEV model using statistical data. The results show 2.16 kWh/mile using the statistical data vs. 2.17 kWh/mile using ORNL s-by-s driving data, meaning less than 1% error, again implying that these BEV methodologies and assumptions are reasonable.

For BEV charging in the simulations, all MD/HD battery electric vehicles are assumed to be fully charged every morning before beginning daily service. En-route charging is considered during the period of vehicle daily route operation. However, the en-route charging strongly depends on MD/HD vocations and driving patterns. For example, Class 8 port drayage tractors

frequently upload, drive, and download cargoes between airport/seaport and warehouse, and stop/waiting time at airport/seaport and warehouse represent fairly good opportunities for recharging; school buses typically travel one or two routes in the morning and again in the afternoon, and there is adequately time for recharging before serving afternoon activities. Similarly transit bus and delivery trucks and vans typically experience significant time at bus depots, marketplace delivery stops and so on. These are all good opportunities for battery recharging through appropriate regular charging or wireless charging technologies during the slots. However, utility trucks usually require immediate travel to any unscheduled site for emergency service, so en-route recharging for utility trucks during their travel is not appropriate. Consequently, Table 4 lists our charging assumptions for the modeled vehicles after considering their actual drive patterns. Except school bus, drayage, refuse and utility trucks, a vehicle stop of more than 5 minutes provided by Fleet DNA is considered to be a charging event. Also, as shown in Table 1, charging power technologies vary with different BEV manufacturers and MD/HD applications, covering 0.2 - 5hrs charging time. To simplify the current electrification studies and analyses, we consider a fast recharging technology which enables 45 minutes to complete full battery charging, but also limits the maximum charging power to not more than 480kW. Thus, the considered charging power is between 25 and 480 kW, depending on battery size and vehicle type. The charger efficiency is assumed as 97% for charger power with 80 kW or higher; otherwise it is 85%. The considered charger efficiency is the overall energy efficiency of the charging procedure from grid electrical energy at charging facility to BEV battery. The efficiency does not account for grid distribution losses.

RESULTS AND DISCUSSIONS

Impact of BEV Service Coverage

As discussed above, the most extreme service days covered by MD/HD conventional vehicles often accounts for a very small percentage of total vehicle miles. Therefore, excessive battery capacity and cost penalties can be avoided very well with little to no impact on service provision for fleets if electric vehicles are not required to cover all service-days in the data set. Instead, conventional vehicles are used to satisfy such extreme service days. Therefore, we focus on evaluating battery capacity need for 50-90% service coverage. The service coverage of less than 50% is not considered is because it may limit substantial BEV applications due to inadequate service opportunities. Service coverage represents the percentage of all operating days in a year. For example, 50-90% service coverage means the service covers 50-90% of all operating days in a year. The results are plotted in Figure 2, showing that Class 7-8 HD vehicles require considerably larger battery capacity than Class 3-6 MD vehicles. For 90% service coverage, the battery requirement of Class 7-8 vehicles is 250-600kWh, as is less than 60kWh for Class 3-6 vehicles. The lower service coverage enables a vehicle to have reduced battery capacity, particularly for Class 7-8 vehicles. When Class 7-8 HD BEV service coverage is reduced down to 50%, the battery capacity requirement of Class 8 port drayage tractors, Class 8 refuse trucks, Class 7 food delivery tractors, and Class 7 city buses is only 20%-57% of the battery needed for their 90% service coverage. This significant reduction of battery cost indicates a considerable potential of Class 7-8 HD electrification applications for short-distance service. For Class 3-6

MD vehicle, the similar service coverage reduction does not lead to a battery reduction as large as Class 7-8 HD vehicles. This is because the battery size used in Class 3-6 MD electrification is usually a smaller capacity than Class 7-8 MD vehicles (see Figure 2(a)).

On the other hand, for the MD/HD electric vehicles with 50-90% service coverage, the smaller battery capacity leads to less average daily service mileage, shown in Figure 2(b). Corresponding to substantial battery capacity reduction to HD BEVs with less service coverage, the daily service mileage of the HD electric vehicles is also considerably reduced. For Class 3-6 MD vehicles, their average daily service mileage does not decrease very much, although their service days are decreased (see Figure 3). Figure 3 shows totals of 245 and 136service days for conventional MD and HD food delivery trucks, respectively. With the range of 50, 75, 90% service coverages, the class 5 food delivery electric trucks cover 123, 184, and 220 days of service, respectively; and class 7 food delivery electric trucks can cover 68, 102, and 122 days of service, respectively. For HD applications, the uncovered services are caused typically by aggressive daily driving mileage (i.e., >450 miles) or longer driving per stop charging (i.e., >75 miles/stop charging). A similar phenomenon occurred with MD BEVs. Therefore, it is important for MD/HD vehicle electrification to appropriately alter EVs driving patterns for fitting well-planned short route and unique en-route charging activities in order to achieve successful MD/HD vehicle electrification with reasonable battery size.

Figure 4(a) reveals the energy consumption comparison between conventional and battery electric vehicles. The results show all the battery electric vehicles achieve 11-34% and 68-80% energy consumption savings compared to conventional vehicle engine-out mechanical energy and fuel energy, respectively. The significant energy savings is mainly due to BEV braking energy recovery, energy reduction at idling, and accessary load reduction, as have been well addressed in previous works [3, 22]. To well understand the energy consumption savings related to BEVs, we converted BEV battery electric energy consumption into diesel- equivalent fuel economy. The BEV diesel equivalent fuel economy is calculated based on the assumption that diesel is used as fuel in a power plant with 45% efficiency, and the produced electricity is delivered to a charging station with 95% distribution efficiency. Thus, compared to the identical conventional vehicles, the projected equivalent fuel economy improvement is 34-77% in the BEV scenario with 75% service coverage (see the details of Figure 4(c)). Figure 4(b) displays the energy cost savings of MD/HD BEVs in unit of $/mile. The BEVs save 55-69% of the energy cost compared to the identical diesel vehicles. In the calculations, the used diesel fuel price is $2.577 per gallon, which is the average U.S. market price of diesel as of February 2017 [26]. The price for electricity is 9.4 cents per kWh, which is the average U.S market cost of electricity for December 2016 [27]. In general, both MD and HD vehicle electrifications achieve significant energy cost savings. A similar conclusion has been reported in [3].

Discussion on Payload Limit and Payback Period

EV batteries typically lead to significant weight penalties due to low battery energy densities. It is important to understand how much the mass penalty could be increased due to electrification. Figure 5(a) shows the BEV mass penalty for MD/HD vehicles as a function of different service coverages. Clearly the mass penalty is significant for HD applications with 90% service coverage. Class 7 food delivery truck electrification with 90% service coverage requires ~600 kWh battery capacity and results in a 3,500kg mass penalty. The mass penalty certainly reduces the delivery truck payload, meaning more BEVs are needed than conventional vehicles to complete the food delivery. However, with less service coverage leading to less battery need, the

mass penalty is considerably decreased. Therefore, it deserves future studies for the optimization among service coverage, battery size, and payload reduction. MD vehicle electrification causes no more than 160kg mass penalty which should not impact vehicle payload. With less service coverage, the mass penalty could even be eliminated. The reason is mainly because of smaller MD BEVs' battery size (see Figure 2(a)).

The earlier simulations show MD/HD vehicle electrification leads to energy savings, but significant battery capacity requirement leads to high BEV purchase cost. Thus, it is particularly interesting to understand the payback period for these MD/HD vehicle electrifications. In the cost effectiveness analysis, the 2016 US DOE projected prices for Li-ion batteries, electric motors, and power electronics [28-29] were used, while open literature cost data [30-31] are used for conventional power devices like engines, clutches, transmissions, and aftertreatment systems. Similar to Eq. 8, the cost penalty for MD/HD electrification is estimated based on the cost variance between E-Powertrain cost and conventional powertrain cost. The cost penalty is further used with annual travel mileage related to various service coverage scenarios and energy cost savings shown in Figure 2 to determine the potential payback period of each MD/HD BEV. The annual travel mileage of various service coverage BEVs is based on the corresponding reduced daily service mileage for a year of 365day operation; in other words, the BEVs with less service coverage are designed to provide year-around short-distance service. The results are plotted in Figure 5(b). Although higher service coverage leads to a longer payback period, the majority of MD BEVs except Class 3 bucket trucks achieve less than a 5-year payback period, particularly true for the 50-75% service coverage. For HD BEVs, except Class 8 port drayage tractors, the 90% service coverage results in a 10-year or even longer payback period, but the 50% service coverage just requires 7-8 years. For Class 8 port drayage tractor, it should achieve no more than a 3.5-year payback period for 50-75% service coverage. One explanation could be due to the unique driving feature of port drayage tractors which frequently drive from ports to ports or warehouses. It is clear that there is good potential for Class 8 port drayage tractor electrification based on cost effectiveness.

All the cost effective analyses do not consider the cost related to repair, maintenance, and battery disposal. In addition, all the above analyses do not consider the impact of climate (i.e. cold and hot weather) and ambient temperature on BEV driving range and cost effectiveness. We agree the impact is important and deserves study in future work. However, a comprehensive discussion in this paper is beyond the scope of the current study.

CONCLUSION

A wide-range of analysis of Class 3-8 commercial vehicle electrification has been conducted by means of developing a framework tool which adopts a quantitative method of estimating electric vehicle energy consumption and appropriate charging considerations using the Fleet DNA composite statistics on driving behavior. The developed tool provides insights into BEV feasibility and cost-effectiveness across types and duties of MD/HD vehicles, and identifies high-potential MD/HD electrification technologies and market opportunities. In the paper, the ten representative Class 3-8 commercial vehicle electrifications have been evaluated and reported as a function of various service coverages, including applications in port drayage tractors, refuse trucks, delivery trucks, buses and bucket trucks.

The results demonstrate Class 7-8 HD vehicles require considerably larger battery capacity compared to Class 3-6 MD vehicles. For 90% service coverage, Class 7-8 BEVs need a

250-600kWh battery compared to less than 60kWh for Class 3-6 vehicle. The mass penalty is also significant for the HD applications with 90% service coverage and could impact vehicle payload. However, less service coverage enables a meaningful reduction of battery capacity and mass penalty for Class 7-8 vehicles, but not for Class 3-6 MD vehicles. This indicates a high potential of Class 7-8 HD electrification applications for short-distance service with lower battery capacity needs. Class 3-6 MD vehicles seem more feasible for vehicle electrification with reasonable battery size and greater service coverage.

Moreover, MD/HD vehicle electrification results in significant energy savings and fuel cost savings. The projected diesel-equivalent fuel economy of BEVs represents a 34-80% improvement and saves 55-69% in fuel energy cost compared to the comparable diesel vehicles. In considering payback, the cost effectiveness analysis illustrates that higher service coverage leads to longer payback years due to higher battery capacity requirements. The majority of MD BEVs, except Class 3 bucket trucks, achieve better than a 5-year payback, particularly for the 50-75% service coverage. For HD BEVs, except Class 8 port drayage tractors, the 90% service coverage results in a 10-year or longer payback period while the 50% service coverage yields a 7-8 year payback. Class 8 port drayage tractors should achieve payback in no more than 3.5 years for 50-75% service coverage.

Overall, MD vehicle electrification provides more feasible opportunities with less battery cost, payback period and similar energy savings. However, various MD/HD vehicles have different operations and drive patterns, which may lead to different cost and energy saving scenarios in terms of electrification. In particular, this requires a further optimization study with evolving battery and infrastructure technologies.

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TABLE 1: MD/HD vehicle electrification technologies and readiness [7-8, 16-18]

Type	Vehicle	OEM	Battery (kWh)	Range (miles)	Charging (kW or hr)
Transit Bus[a]	30-60ft city bus	BYD Motors	197-591	120-200	80-200
	35-60ft city bus	New Flyer	100-480	120	-
	35-40ft city bus	Proterra	79-660	47-350	0.2 -5 hrs
	40ft city bus	Nova	-	15	-
	40ft city bus	GreenPower	320	>185	-
	Shuttle bus	Balqon	-	100-150	-
	Shuttle bus	Phoenix	-	100	-
	Shuttle bus	Motiv	-	65-100	60
School Bus[b]	School bus	Lion	90/105/130	50-100	-
	School bus	Motiv	85/106/127	65 - 100	25
	School bus	TransPower	108	75	1.5-2.0 hrs
	School bus	Adomani	210-400	>175	-
MD truck[b]	Delivery van	AMP	60	60	-
	Delivery van	Motiv	85/106/127	65 - 100	25
	MD cargo van	Zenith Motors	52-62	90	6
	Class 5 delivery truck	BYD Motors	145	155	100
	Class 6 delivery truck	BYD Motors	175	124	100
	MD work truck	Motiv	85/106/127	65 - 100	-
	MD terminal truck	Orange EV	80-160	-	-
	MD utility truck	Phoenix	105	100	2.5-3 hrs
HD truck[c]	Class 7 Semi-tractor	Cummins	140kWh	100	1 hr
	Class 8 tractor	TransPower	-	-	-
	Class 8 refuse truck	Motiv	170-212	50 - 80	45
	Class 8 tractor	BYD Motors	188	92	80
	Class 8 drayage	Balqon	140-250	150	-

[a]: Commercially available; [b]: Limited Commercial Availability; [c]: Demonstration Phase

TABLE 2: Ten representative Class 3-8 MD/HD vehicle driving behavior summary.

Drive Characteristics Summary	Class 8 Drayage Tractor	Class 8 Refuse Truck	Class 7 Food Delivery Tractor	Class 7 City Transit Bus	Class 6 School Bus	Class 5 Linen Delivery Van	Class 5 Food Delivery Truck	Class 4 Parcel Delivery Van	Class 3 Food Delivery Truck	Class 3 Bucket Truck
Average Drive Disitance (mile/day)	119	73	164	102	61	66	40	55	37	26
Annual Travel Mileage [a]	43386	26566	60001	37284	22112	23992	14478	19911	13551	9652
Max Drive Distance (mile/day)	612	273	568	268	181	141	81	132	79	93
Average Drive Time (hr/day) [b]	4.29	3.52	4.36	5.05	2.09	2.42	1.18	2.79	1.12	1.09
Max Drive Time (hr/day) [b]	13.80	8.78	11.52	13.80	4.52	4.21	2.05	4.56	2.14	2.61
Average VehicleOn Time (hr/day) [c]	9.06	7.33	7.26	9.11	2.96	6.18	2.98	7.06	1.60	3.10
Max VehicleOn Time (Hr/day) [c]	23.96	13.21	15.69	22.35	7.73	12.63	18.16	11.38	3.29	8.52
Average Drive Speed (mph) [b]	27.70	20.68	37.71	20.23	23.54	27.18	33.52	19.57	33.19	24.35
Max Drive Speed (mph) [b]	76.50	69.59	71.87	69.07	79.24	69.90	70.66	70.84	70.34	74.63
Average VehicleOn Speed (mph) [c]	14.11	9.46	18.93	11.36	17.74	11.87	18.23	8.30	22.84	10.75
Average Stops per Mile	1.02	4.01	0.49	1.72	1.40	1.49	0.78	3.33	0.81	1.74
Max Stops per Mile	13.37	16.75	8.45	4.76	3.86	3.02	3.04	6.58	3.03	3.13
Average Stops per Day [d]	7.10	3.00	10.68	3.32	2.00	13.96	8.58	9.42	8.89	7.74
Max Stops per Day [d]	28.00	3.00	23.00	14.00	2.00	30.00	16.00	28.00	17.00	20.00

[a]: 1 year = 365 days; [b]: Vehicle speed >0; [c]: Vehicle speed ≥0; [d]: stop or idling time >5 minutes.

TABLE 3: Key parameters used for modeled conventional and battery electric vehicles.

Vehicle Type	Class 8 Port Drayage Tractor	Class 8 Refuse Truck	Class 7 Transit City Bus	Class 7 Food Delivery Tractor	Class 6 School Bus	Class 5 Linen Delivery Van	Class 5 Food Delivery Truck	Class 4 Parcel Delivery Van	Class 3 Bucket Truck	Class 3 Food Delivery Truck
C_d	0.65	0.82	0.79	0.65	0.80	0.55	0.55	0.55	0.50	0.46
C_{rr}	0.0080	0.0098	0.0098	0.0080	0.0090	0.0095	0.0095	0.0095	0.0110	0.0120
Frontal Area (m^2)	8.5	8	8.2	8.2	8.2	6	6	6	4	5
Veh weight (kg)	34545	23823	13000	12727	11818	8377	8208	7273	5909	5909
Eng eff	0.36	0.32	0.32	0.328	0.32	0.32	0.32	0.32	0.32	0.32
Gear Box Eff	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92
Final Drive Eff	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98
Wheel Eff	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
Motor Eff	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88
Battery Eff	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98
Conv_Acc (kw)	4	6	12	8	6	2	5	2	4	4
EV_Acc (kw)	2	3	6	4	3	1	2.5	1	2	2

TABLE 4: Charging assumption for the modeled vehicles.

Charging assumption	Charging Event	Charging Time (s)
Class 8 Drayage Tractor	Data*	1800
Class 8 Refuse Truck	2	600
Class 7 Food Delivery Tractor	Data*	300
Class 7 City Bus	Data*	300
Class 6 School Bus	1	7200
Class 5 Linen Delivery Van	Data*	300
Class 5 Food Delivery Truck	Data*	300
Class 4 Parcel Delivery Van	Data*	300
Class 3 Food Delivery Truck	Data*	300
Class 3 Telecom Truck	0	0

* Based on stop times >300s provided in Fleet DNA data

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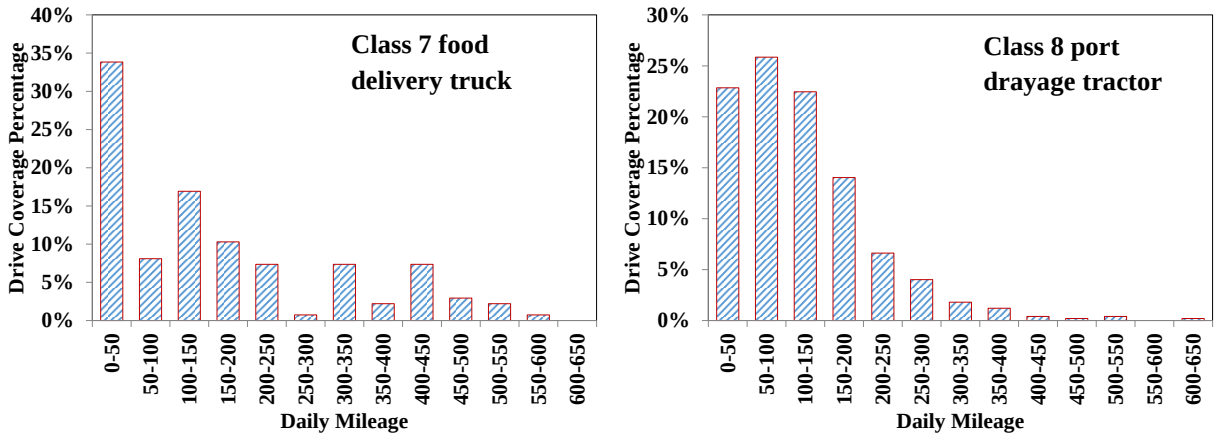
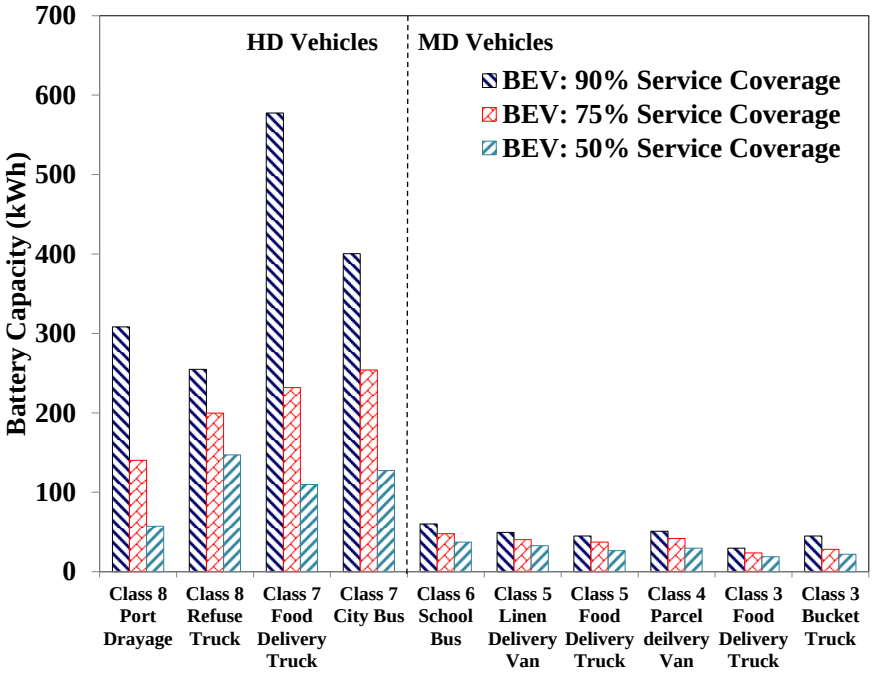
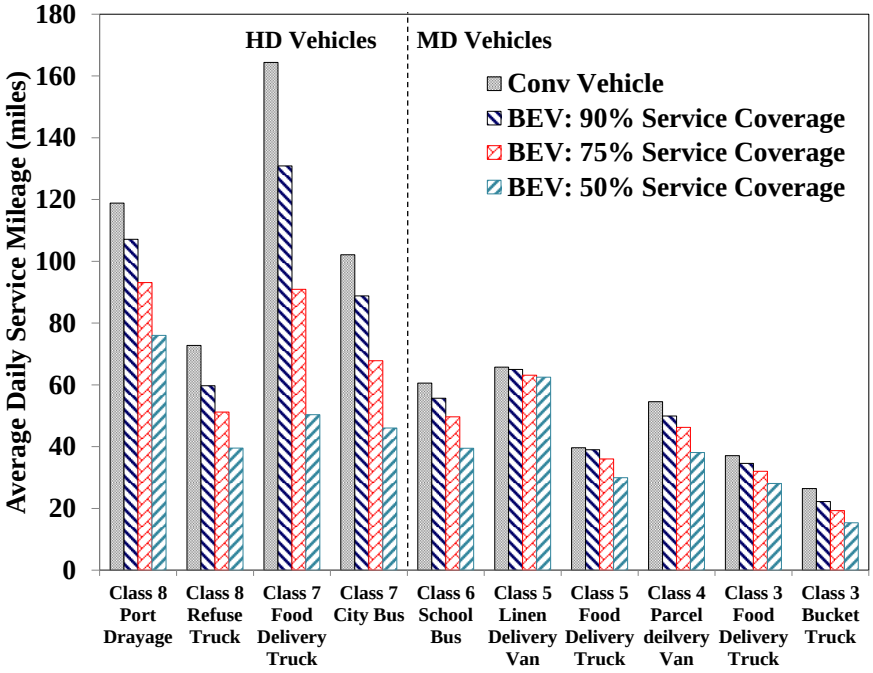


FIGURE 1: Driving statistics of Class 7 food delivery and Class 8 port drayage tractors.

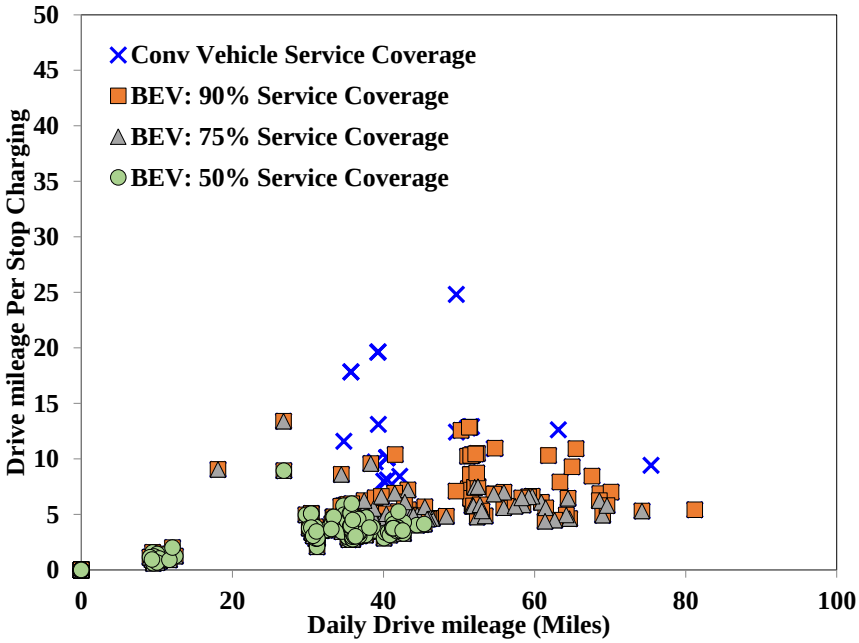


(a) Battery capacity

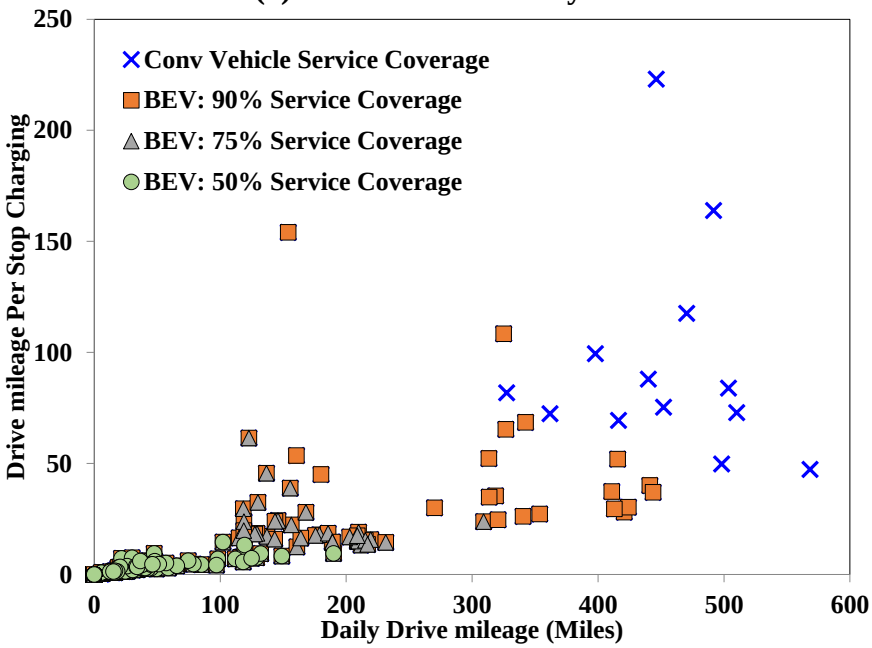


(b) Daily service mileage

FIGURE 2: Effect of MD/HD vehicle electrification for 50-90% service coverage on battery capacity requirement and daily service mileage. En-route charging is considered with 45 minutes of full battery charging, except bucket trucks.

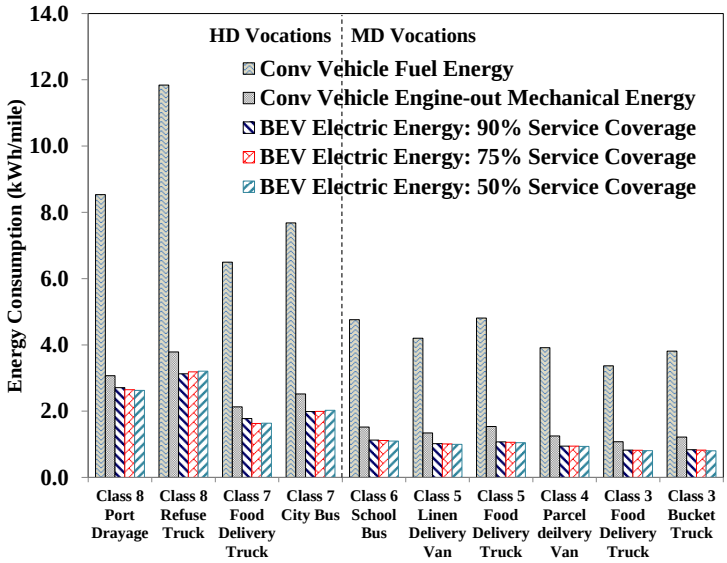


(a) Class 5 food delivery truck

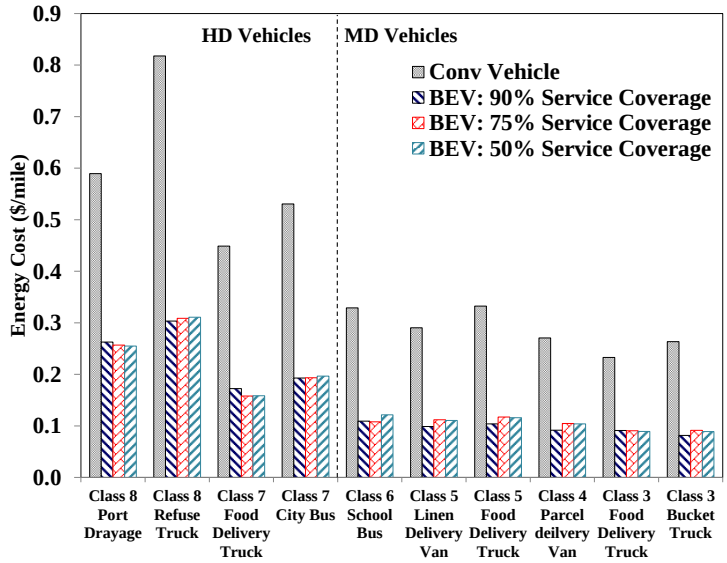


(b) Class 7 food delivery truck

FIGURE 3: The service days and driving mileage per charging stop of class 5 and class 7 food delivery electric trucks with 50-90% service coverage. En-route charging is considered with 45 minutes of full battery charging. Each distributed point represents a day of driving.



(a) Energy Consumption

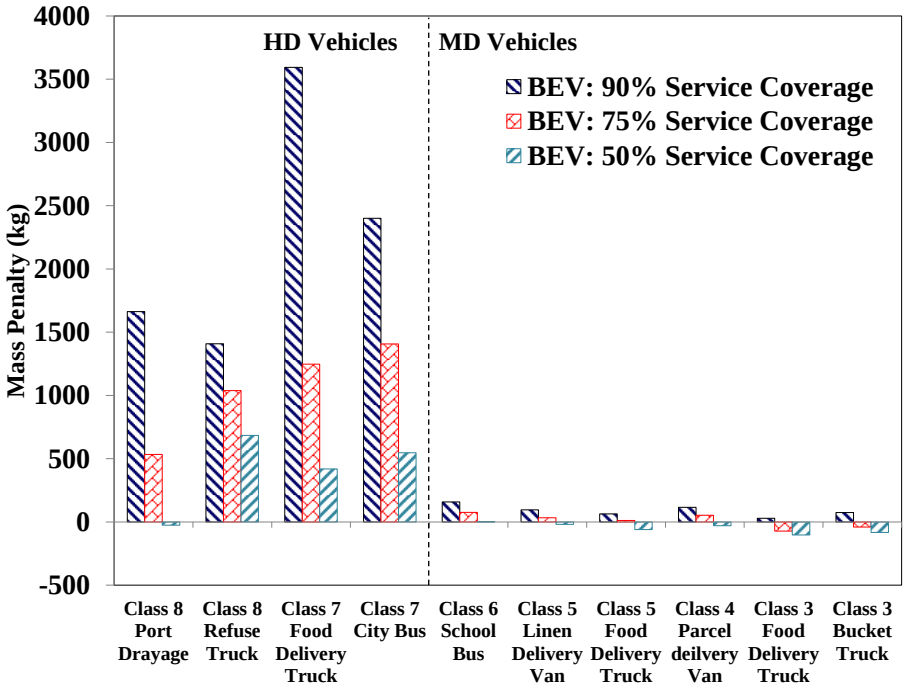


(b) Energy Cost

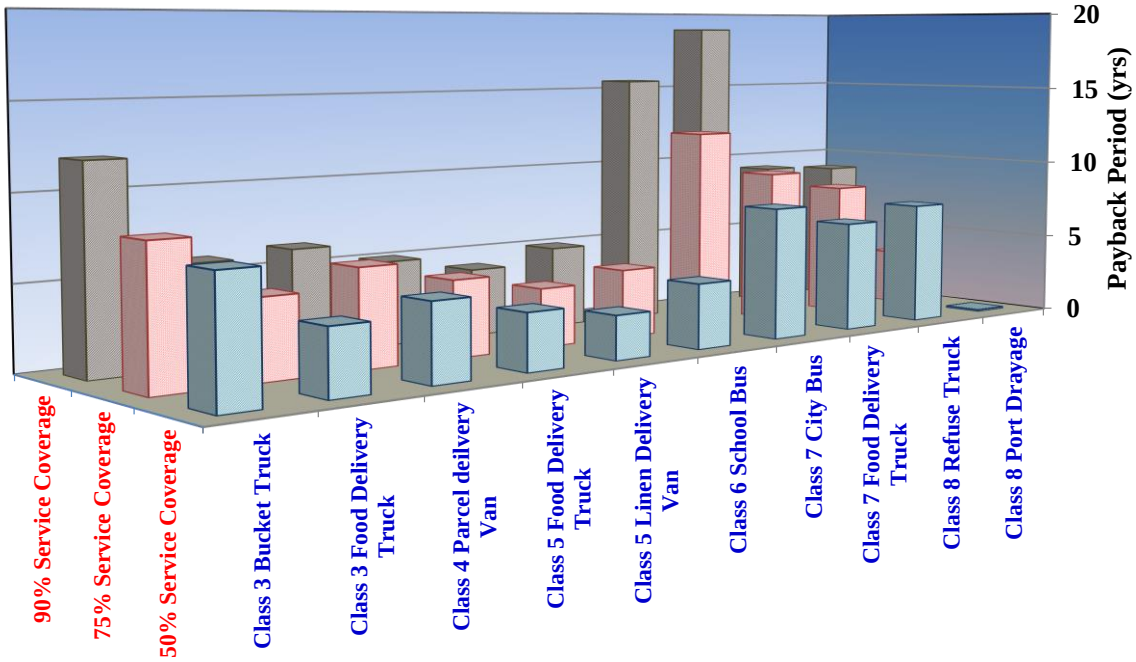
MD/HD Electrification: 75% service coverage	Eng-out Energy (kWh/mile)	Fuel Economy (mpg)	Battery Energy (kWh/mile)	Equivalent Fuel Economy (mpg)
Vehicle	Conventional vehicle		BEV	
Class 8 Port Drayage	3.1	4.4	2.7	5.8
Class 8 Refuse Truck	3.8	3.2	3.2	4.9
Class 7 Food Delivery Truck	2.1	5.7	1.6	9.5
Class 7 City Bus	2.5	4.9	2.0	7.7
Class 6 School Bus	1.5	7.8	1.1	13.9
Class 5 Linen Delivery Van	1.3	8.9	1.0	13.4
Class 5 Food Delivery Truck	1.5	7.8	1.1	12.8
Class 4 Parcel delivery Van	1.3	9.5	0.9	14.3
Class 3 Food Delivery Truck	1.1	11.1	0.8	16.5
Class 3 Bucket Truck	1.2	9.8	0.8	16.4

(c) Diesel Equivalent Fuel Economy

FIGURE 4: Energy consumption, energy cost and fuel economy of MD/HD conventional vehicles and electric vehicles with 50-90% service coverage. En-route charging is considered with 45 minutes of full battery charging except bucket truck.



(a) BEV mass penalty



(b) BEV payback period

FIGURE 5: BEV mass penalty and payback period of MD/HD electrification as a function of various service coverages. En-route charging is considered with 45 minutes of full battery charging, except bucket trucks.