# Estimating Maintenance and Repair Costs for Battery Electric and Fuel Cell Heavy Duty Trucks

## A STEPS+ Sustainable Freight Research Program Technical Paper

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# Contents

# 1. Introduction

Truck maintenance and repair (M&R) costs are an important component of owning and operating trucks, but the topic has not been well studied. Currently there is very limited data on such costs for advanced powertrain systems, especially in heavy duty applications. This study develops an exploratory method to estimate M&R costs for battery electric and fuel cell heavy duty trucks.

## 1.1. Background

Truck M&R costs, sometimes referred to simply as maintenance costs, reflect the cost of labor and parts for the following components (Barnes and Langworthy, 2003; CARB, 2019):

- planned or routine maintenance, such as tire rotation, engine oil change, coolant inspection, and other routine work;
- unanticipated repairs, such as fixing the exhaust system, replacing broken headlight bulbs, and repairing other broken components; and
- tire replacement, due to tire wear. This is sometimes broken out as a separate category from maintenance and repairs as this single item makes up a significant portion of the overall M&R cost over the lifetime of the vehicle.

M&R costs, fuel consumption, and vehicle depreciation are collectively referred to as the vehicle operating costs which are an important economic indicator for vehicles (Barnes and Langworthy, 2003). In contrast, according to AAA's calculation method, the operating costs are calculated as fuel costs plus maintenance, repair, and tires costs (AAA, 2020). In either coverage of the operating cost calculations, the M&R costs must be considered for a complete vehicle and fuel system cost model.

Total M&R costs include the price of parts and the cost of labor. By definition, the common metric expression is written as follows (Eudy and Post, 2021):

$$\text{Cost per mile} = [\text{Parts cost} + \text{Labor rate (\$/hour)} \times \text{Labor hours}] \,/\, \text{mileage}$$

The defined expression applies not only to trucks but also cars. Based on AAA's Your Driving Costs annual statistics for owning a car, costs for maintenance, repair, and tires are 9¢/mile in 2020, a 4% increase year over year, reflecting an increase in the national labor rate (AAA, 2020).

In practice, original data on M&R costs are commonly collected from surveying truck original equipment manufacturers (OEMs) and fleet owners or operators (Williams and Murray, 2020).

There is little or no data on M&R costs for advanced heavy duty (HD) technologies such as battery electric vehicles (BEVs) and fuel cell vehicles (FCVs), while some data is available for conventional diesel trucks and passenger cars. However, it may not work well to simply assume the diesel trucks’ M&R costs can represent alternative fuel trucks, as often can be seen in the literature, because M&R needs and patterns differ widely between different truck types and technologies.

From the temporal perspective, HD M&R costs will also be significantly different during transition and in full deployment for advanced technologies which are currently still in the early market years of deployment. In addition to current cost levels, a fair cost comparison should also examine the M&R costs of new technologies in the context of a future mature market.

In summary, HD truck M&R costs by technology (i.e., diesel, battery electric, and fuel cell) may play an increasingly important role when making a complete comparison between conventional and advanced technologies. This study will develop an exploratory method to estimate M&R costs for battery electric and fuel cell trucks. The developed method and data will facilitate the estimation of the total cost of ownership (TCO) for researchers and policymakers by taking into consideration the M&R costs, in addition to the vehicle capital costs and the fuel costs.

### 1.2. Study Objectives

This study aims to develop M&R cost values on a per mile basis for battery electric and fuel cell HD trucks, while considering the difference in current and future market adoption. In particular, the study will:

- conduct a literature review on M&R costs for diesel, battery electric, and fuel cell HD applications;
- develop a component level cost method to quantify the M&R costs for battery electric and fuel cell HD trucks;
- apply the learning curve effect to address the potential difference in current and future M&R costs; and
- perform an assessment through the literature review whether the costs for an engine rebuild, a battery replacement, or a fuel cell stack refurbishment should be accounted for in HD truck TCO studies.

## 2. Literature Review

### 2.1. Literature on M&R Costs for Heavy Duty Trucks

This study takes advantage of diesel M&R cost values as the benchmark for comparison with other technology HD trucks. Historical M&R cost statistics are well documented for HD diesel trucks. For example, American Transportation Research Institute (ATRI) regularly releases its annual updated report on the operational costs of trucking including diesel long-haul trucks. There is less discrepancy in M&R cost values for conventional diesel long-haul trucks than for other truck type and fuel combinations, as can be found by reviewing a variety of literature sources such as ATRI reports and the AFLEET model (Williams and Murray, 2020; Burnham, 2020). Therefore, this study will use the HD long-haul diesel truck as the reference vehicle and, starting with it, estimate the M&R costs for advanced technology trucks.

Figure 1 presents historical M&R cost statistics for HD tractor-trailer diesel trucks, based on the ATRI data including tire replacement costs (Williams and Murray, 2020). Results indicate that HD diesel M&R costs vary with year, typically around $0.20/mile. Socioeconomic and behavioral changes could affect the cost-per-mile metric year by year. For example, M&R costs decreased considerably in 2019, compared to the 2018 level, because of less freight trucking activity in 2019 due to the China-United States trade war (Williams and Murray, 2020).

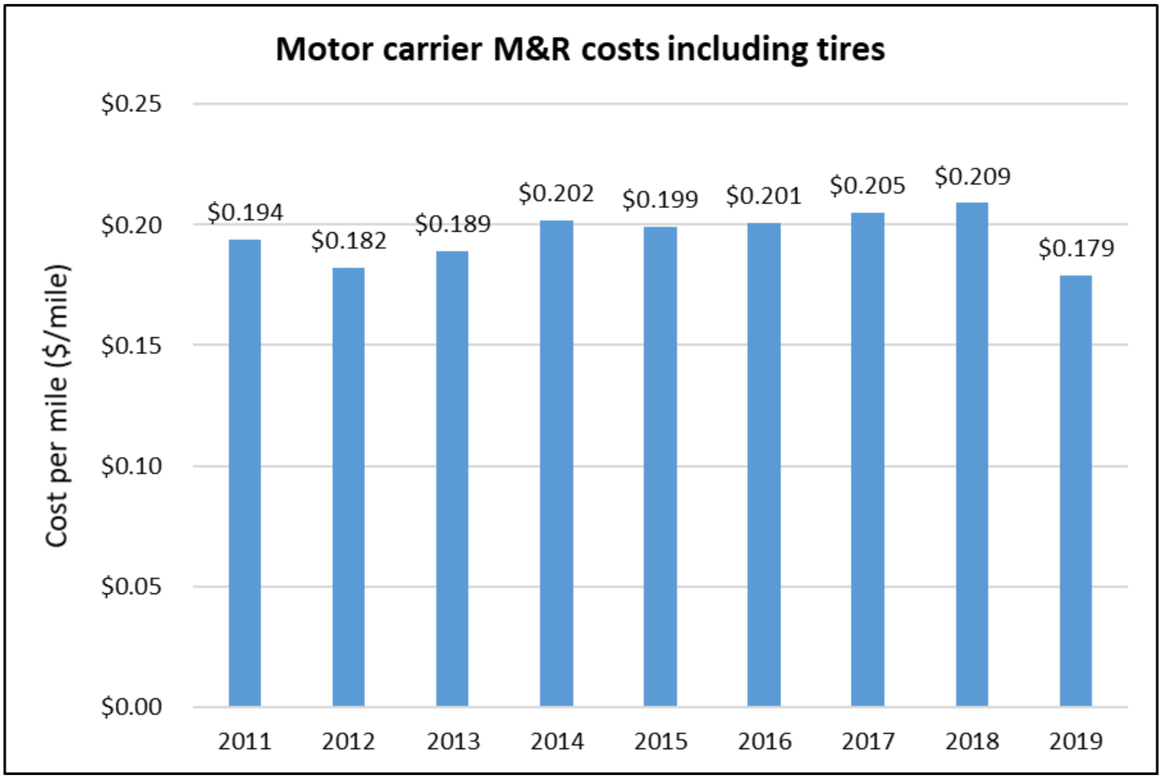


Figure 1. Historical M&R cost statistics for heavy duty diesel trucks (Williams and Murray, 2020)

Propfe et al. (2012) analyzed the TCO comparison of different electrified propulsion technologies for the German car market in 2020, with detailed M&R costs estimated on a component level. Currently, it is one of the very few studies that presents M&R costs for BEVs and FCVs, in addition to conventional internal combustion engine (ICE) cars, as well as regular and plug-in hybrids. The study is based on light duty vehicles but certainly can provide some insights into how we look into the advanced heavy duty propulsion technologies.

Due to the reduced complexity of the powertrain and fewer moving parts, electrified propulsion technologies, such as BEVs and FCVs, will have lower maintenance requirements and tend to result in a lower overall M&R cost, compared to conventional vehicle technologies (Propfe et al., 2012; CARB, 2019; DOE, 2008). Propfe et al. (2012) compared 31 individually assessed vehicle components, as shown in Figure 2, and found that M&R costs for full electric vehicles like BEVs and FCVs tend to be driven by major components (e.g., the traction battery or the fuel cell system). In addition, Figure 2 also shows that BEVs and FCVs have less M&R costs associated with the braking system and the transmission system, compared to conventional ICE vehicles or hybrids. Put another way, the diesel trucks have relatively complicated transmission and braking systems which likely result in more M&R needs than BEVs or FCVs would.

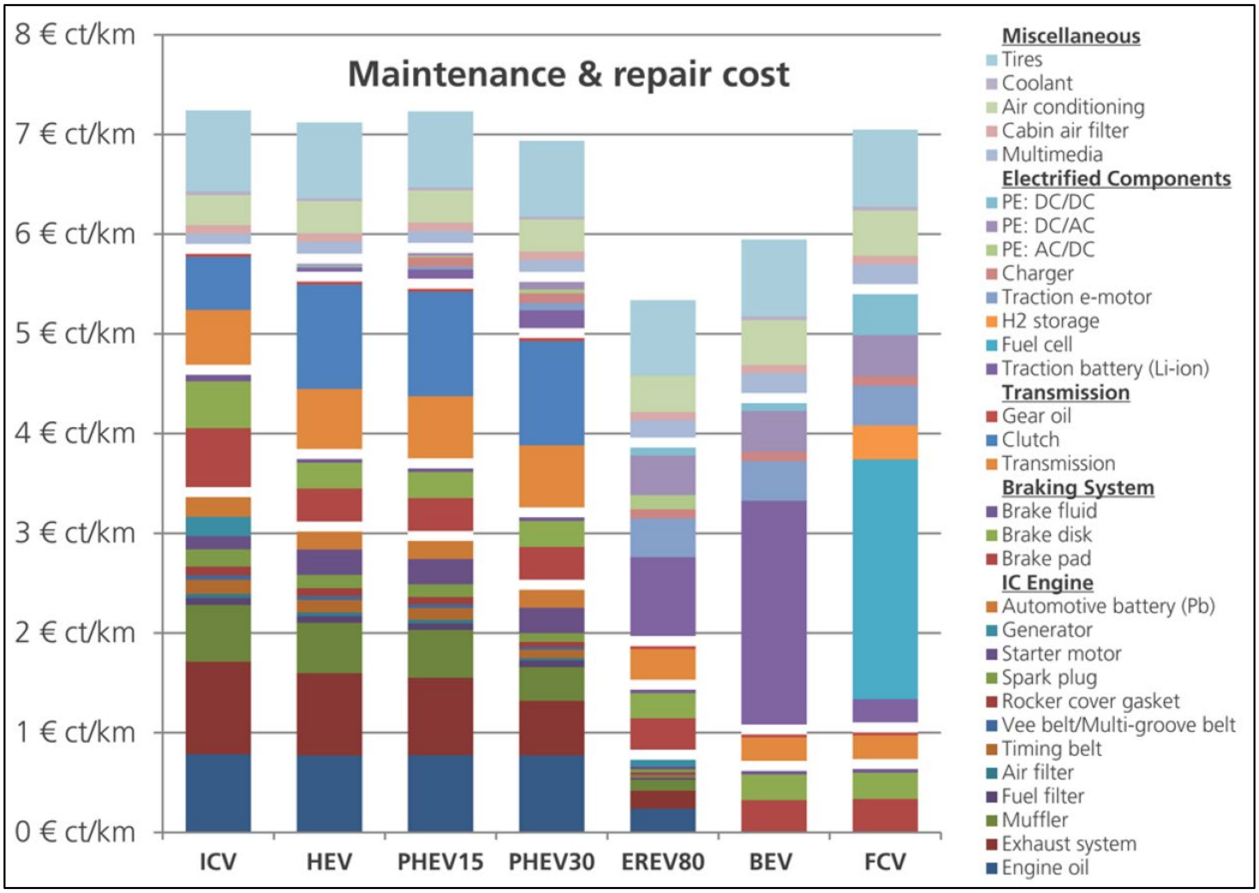


Figure 2. Composition of M&R costs based on all 31 assessed powertrain components (Propfe et al., 2012). Note that the monetary units are Euro cents/km.

California Air Resources Board (CARB) conducted an analysis to estimate the TCO for the Advanced Clean Trucks program, assuming BEVs have a 25% lower maintenance cost than its diesel counterpart (CARB, 2019; CARB, 2021). Due to the lack of data, hydrogen FCVs were assumed to have a maintenance cost equivalent to diesel in the earlier CARB study (2019) but equivalent to BEVs in the recent CARB study (2021). Table 1 shows the maintenance cost assumptions for class 8 trucks in the recent CARB study (2021).

Table 1. Maintenance cost assumptions for the class 8 cabs (CARB, 2021)

| Maintenance cost | Diesel | Battery Electric | H2 Fuel Cell |
|---|---|---|---|
| Class 8 Day Cab ($/mile) | $0.198 | $0.149 | $0.149 |
| Class 8 Sleeper Cab ($/mile) | $0.159 | $0.119 | $0.119 |

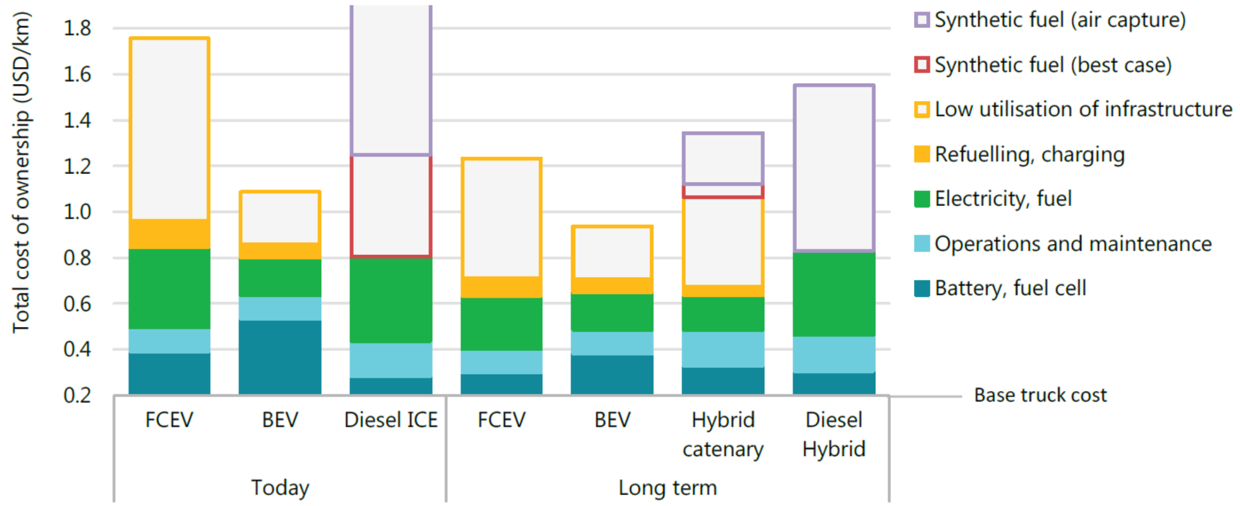
Although maintenance costs are unknown for fuel cell trucks as the supply chain and service networks are not yet fully mature, a U.S. Department of Energy (DOE) technical targets study indicated an industry belief that ultimately the fuel cell powertrain maintenance costs would fall between battery electric and diesel powertrain maintenance costs (Marcinkoski et al., 2019). However, this DOE study itself assumed maintenance costs for class 8 long-haul tractor-trailers to be $0.17/mile for both the diesel and the hydrogen ultimate target cases.

UC Davis researchers conducted a cost comparison of zero-emission highway trucking technologies and used 104,000 miles/year or 500 miles/day, along with the cost-per-mile values, to come up with the annual maintenance costs for long-haul trucks (Zhao et al., 2018). Table 2 shows the M&R cost assumptions for the considered future zero-emission trucking options (Zhao et al., 2018). These cost estimates are based on large scale deployment of vehicles and energy infrastructure, focusing on longer-term possibilities.

Table 2. Cost assumptions for future zero-emission long-haul trucking technologies (Zhao et al., 2018)

| Long-Haul Truck Technology | Conventional Diesel | H2 Fuel Cell | Catenary Electric | Dynamic Charging |
|---|---|---|---|---|
| Truck Maintenance Cost ($/mile) | $0.07 | $0.05 | $0.035 | $0.035 |
| Truck Tires ($/mile) | $0.04 | $0.04 | $0.04 | $0.04 |
| Total M&R Cost ($/mile) | $0.11 | $0.09 | $0.08 | $0.08 |

The International Energy Agency (IEA) study on the future of hydrogen reported TCOs by powertrain for long-haul trucks, and the TCO comparisons between current and future technologies are shown in Figure 3 (IEA, 2019). One of the cost components is the “Operations and Maintenance” cost, which is essentially the M&R cost since the electricity or fuel cost is broken out and not captured in the term. In this IEA study, the maintenance costs for BEVs and FCVs appear the same based on Figure 3, approximately $0.10/km or $0.16/mile for both today and the long-term future.



Notes: The y-axis intercept of the figure corresponds to base vehicle "glider" plus minor component costs. Infrastructure covers stations, charging points and catenary lines. More information on the assumptions is available at www.iea.org/hydrogen2019.

Figure 3. Current and future TCO of fuel/powertrain alternatives in long-haul trucks (IEA, 2019)

The Argonne National Laboratory (ANL) AFLEET model collected a great deal of maintenance (scheduled) and repair (unscheduled) cost values, by a variety of vehicle types (Burnham, 2020). The model is a very comprehensive tool for assessing the TCO of all types of vehicles. However, the datasets embedded in AFLEET have limited M&R cost data on heavy duty BEVs and essentially no data on any hydrogen FCVs (light or heavy duty). Instead, AFLEET assumes FCVs have the same M&R costs as BEVs. In AFLEET, the M&R costs used for long-haul freight trucks are \$0.190/mile for diesel and \$0.173/mile for both battery electric and fuel cell (Burnham, 2020).

Compared with HD truck applications, full electric transit buses such as BEVs and FCVs currently have the most experience in the early stages of heavy duty deployment. Another comprehensive TCO study by ANL researchers indicated that battery electric and fuel cell buses have the M&R benefits of regenerative braking and no exhaust aftertreatment (Burnham et al., 2021). This TCO study assumed that, compared to diesel buses, BEV and FCV buses have the same M&R cost percentage reductions, i.e., 40% lower than diesel.

National Renewable Energy Laboratory (NREL) researchers conducted a financial analysis of battery electric transit buses, and Table 3 summarizes a few baseline parameters for its simple TCO analysis (Johnson et al., 2020). Table 3 suggests that the M&R cost for a battery electric bus is approximately 27% lower than that for a diesel bus.

Table 3. Baseline parameters for battery electric transit buses (Johnson et al., 2020)

| | Units | Value |
|---|---|---|
| Average Annual VMT | miles/year | 32,814 |
| Average Life of Bus | years | 12 |
| Battery Life (BEV Bus) | years | 12 |
| Diesel Bus M&R Cost | $/mile | $0.88 |
| BEV Bus M&R Cost | $/mile | $0.64 |

Another NREL study reported the current status (2020) of fuel cell buses and indicated that the M&R costs for today's fuel cell buses are slightly higher than for diesel buses, possibly because fuel cell buses incur a lot of extra labor hours due to staff training in the early adoption stage although the assumed labor cost rate is as low as $50/hour in this study (Eudy and Post, 2021).

To sum up, currently there are very limited data on M&R costs for battery electric and fuel cell trucks. Even for the transit bus segment which has the most experience in advanced HD technology applications, there is no consensus on the maintenance cost comparison among diesel, battery, and fuel cell buses. One common agreement in the literature is that, in the future, the overall M&R cost for BEVs will be less than or equal to that for FCVs, and both are much smaller than the M&R cost for conventional ICE vehicles, on a cost per mile basis.

## 2.2. Literature on Midlife Overhaul Costs

"Midlife overhaul costs" refers to the cost of rebuilding or replacing major propulsion components of a vehicle due to wear or deterioration, i.e., the cost resulting from an engine rebuild for a conventional diesel vehicle, a battery replacement for a battery electric vehicle, or a fuel cell stack refurbishment for a hydrogen fuel cell vehicle (CARB, 2019; CARB, 2021). The midlife overhaul costs are usually considered separate from the M&R costs and not commonly reported in maintenance cost studies.

Due to the lack of observed cost data, most of the TCO studies do not explicitly consider the engine rebuild cost or the battery replacement cost. As indicated in an ANL study, battery replacement costs for electric drive vehicles are not included in the AFLEET model as there is no reliable data for replacement intervals and expected costs (Burnham, 2020).

A recent CARB TCO study assumed a lifetime mileage of 1.04 million miles for a class 8 sleeper cab tractor, regardless of fuel type (CARB, 2021). The CARB study indicated that the diesel engine of a class 8 heavy duty truck has a useful life of 12 years or up to 800,000 miles; accordingly, an engine rebuild is expected at the end of the engine's useful life. Based on the fact that some electric vehicle manufacturers currently offer a warranty of 8 or more years and up to 300,000 miles, the CARB study assumed that a battery replacement will take place every 300,000 miles (for vehicle model years pre-2030) or every 500,000 miles (for vehicle model years 2030 and thereafter). It also indicated that, according to the estimates from Ricardo, an engineering and energy consultancy, a fuel cell stack refurbishment will be needed after 7 years of operation. However, this CARB study and its prior version reported very different assumptions and results for the midlife overhaul cost (CARB, 2021; CARB, 2019), which appears to be consistent with the point of view that there are no reliable data for replacement intervals and expected costs (Burnham, 2020).

A higher durability of the fuel cell system is required for HD trucks vs. cars, i.e., 25,000 to 30,000 hours for trucks vs. 8,000 hours for cars (Marcinkoski et al., 2019). Table 4 shows the DOE technical system targets for class 8 long-haul tractor-trailers fueled by hydrogen (Marcinkoski et al., 2019). The interim 2030 target for a fuel cell system in HD applications is 1 million miles, which is sufficient to avoid a fuel cell replacement. Furthermore, the fuel cell system lifetime ultimate target of 30,000 hours corresponds to a vehicle lifetime of 1.2 million miles for Class 8 tractor-trailer trucks.

Table 4. DOE technical targets for class 8 long-haul tractor-trailers fueled by hydrogen

| | Units | Interim (2030) | Ultimate (2050) |
|---|---|---|---|
| Fuel Cell System Lifetime | hours | 25,000 | 30,000 |
| Vehicle Lifetime Range | miles | 1,000,000 | 1,200,000 |

The NREL report on the financial analysis of battery electric transit buses used a 12-year battery life, as long as the lifetime of a typical diesel bus (see Table 3 above). The battery life was derived from cycle-based calculations, preliminary field reports, and manufacturer warranties (Johnson et al., 2020). Apparently, there is no need for a battery replacement in the transit bus case. Existing fuel cell bus demonstrations have shown over 30,000 hours operation and provide some confidence that fuel cells can be durable enough for long-haul truck applications as well (Marcinkoski et al., 2019).

The recent ANL cost study assumed no engine rebuild or battery replacement for HD trucks and argued that battery packs and fuel cell systems will last the lifetime of the vehicle; meanwhile, it also acknowledged that there is currently no well-established data on battery pack lifetimes (Burnham et al., 2021).

To sum up, it is uncertain whether heavy duty battery electric or fuel cell trucks will have midlife overhaul costs in a mature market, due to the lack of data on the novel technologies. It is highly likely that there will be no such costs in the long run. Therefore, the midlife overhaul costs are considered beyond the scope of this M&R cost study.

# 3. Methodology

## 3.1. Overview of the Methodology

In this study, we developed an approach to estimating heavy duty M&R costs for advanced technologies. The approach will break down the overall M&R costs into major components and estimate the component level costs across vehicle technologies, with a focus on the technology differences, as shown in Figure 4 (for illustrative purposes only).

The cost estimation approach starts with the reference diesel truck. We assume the overall M&R cost for the diesel truck is $0.20/mile, generally consistent with the literature (Williams and Murray, 2020; Burnham, 2020), and consider it as exogenous to our subsequent calculations.

Using the detailed diesel truck data, we can estimate the common components M&R costs which depend on the magnitudes of the other 3 major components, as shown in the first bar in Figure 4.

Assuming the common components costs keep the same across powertrain technologies, then we only need to make an effort to estimate the M&R costs for the remaining components of battery electric or fuel cell trucks. These components are shown in the second and third bars in Figure 4.

In the end, we simply add up to develop the total M&R cost magnitudes for battery electric and fuel cell HD trucks.

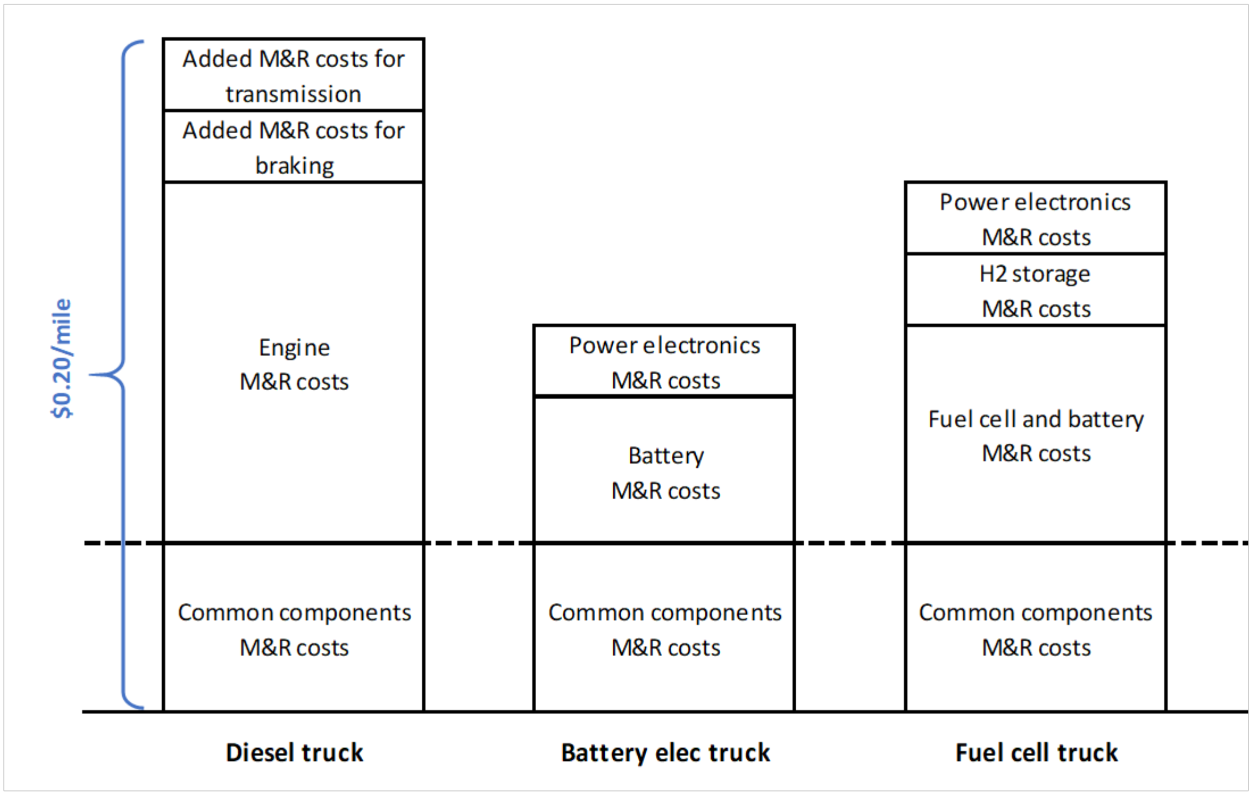


Figure 4. Breakdown of M&R costs into major components across vehicle technologies: a focus on the differences (for illustrative purposes only)

## 3.2. Calculation Steps for the Diesel Truck

M&R cost calculations for advanced technology trucks are based on and linked to the component level results for the reference diesel truck. Calculation steps for the diesel truck are summarized as follows.

1. Determine the total M&R cost for the HD diesel truck. This study uses $0.20/mile, in constant 2020 dollars, which is an exogenous input for subsequent calculations.

2. Calculate cost fractions for the following 4 major components, based on the ICE passenger car's data (Propfe et al., 2012):

    - added M&R costs for transmission, 11%;

    - added M&R costs for braking, 7%;

    - engine related M&R costs, 48%; and

    - common components M&R costs, 33%.

3. Multiply $0.20/mile by each percentage number above to develop cost numbers for each of the 4 components.

4. The developed value for common components will be kept the same and used for BEVs and FCVs.

## 3.3. Calculation Steps for Battery or Fuel-cell Trucks

Recognizing the lack of actual M&R cost data on battery and fuel cell technologies for HD trucks, this approach leverages the existing data on the conventional heavy duty trucks and the light duty BEVs and FCVs, for which there are relatively abundant and reliable cost data in the real world. Calculation steps for the battery and hydrogen technologies are summarized as follows.

1. Extract light duty M&R cost values for each advanced technology component, based on the passenger car's data for BEVs and FCVs (Propfe et al., 2012).

    For BEVs, the advanced technology components are as follows:

    - battery M&R costs, and

    - power electronics M&R costs.

    An analysis shows that long-haul fuel cell trucks need a 300 kW fuel cell to cover a range of 500 miles and, in an optimized efficiency system, a 50 kWh battery is needed to buffer peak power demand (Zhao et al., 2018). This M&R cost study considers the following advanced technology components for FCVs:

    - fuel cell and battery M&R costs,

    - hydrogen storage M&R costs, and
    - power electronics M&R costs.

2. For each cost component above, which corresponds to the light duty vehicles, multiply an adjustment factor of 1.33 to come up with the M&R cost values for HD trucks. The conversion factor of 1.33 is derived from the ratio of the following two well-acknowledged M&R cost values:
    - combination long-haul truck, diesel: $0.20/mile (Williams and Murray, 2020); and
    - passenger car, gasoline: $0.15/mile (Burnham, 2020; Propfe et al., 2012).
3. Add up all cost components to come up with the total M&R costs.

## 3.4. M&R Cost Category Coverage

This study is aimed at developing an analytical approach to estimating the total M&R costs while maintaining a reasonable level of detail. The strategy is to estimate heavy duty M&R cost values at the aggregated major components level, as show in Figure 4. Considering the uncertainty, this study will avoid developing cost numbers for battery and fuel cell technologies at a very detailed level such as the individual parts level.

In practice, the cost categories (i.e., the major cost components) that we have used for HD trucks are consistent with those aggregated from the detailed cost analysis for light duty vehicles as presented in a European study (Propfe et al., 2012). Table 5 shows the M&R cost category coverage and the aggregation mapping based on the European study (Propfe et al., 2012).

The common components category captures identical or similar M&R services including tires across truck technologies, and their costs are assumed the same.

Note that the diesel truck has the added costs (or extra costs) for transmission and braking. They are just another way to say BEVs or FCVs incur less M&R costs for braking and transmission. Certainly, BEVs and FCVs also have their M&R costs for braking and transmission, which, however, are included in the common components category.

Table 5. M&R cost category coverage

<table>
<tr><th>Cost component</th><th>Diesel Truck</th><th>Battery Elec Truck</th><th>Fuel Cell Truck</th></tr>
<tr><td rowspan="11">Common components</td><td colspan="3">Brake fluid</td></tr>
<tr><td colspan="3">Brake disk</td></tr>
<tr><td colspan="3">Brake pad</td></tr>
<tr><td colspan="3">Gear oil</td></tr>
<tr><td colspan="3">Transmission</td></tr>
<tr><td colspan="3">Tires</td></tr>
<tr><td colspan="3">Coolant</td></tr>
<tr><td colspan="3">Air Conditioning</td></tr>
<tr><td colspan="3">Cabin air filter</td></tr>
<tr><td colspan="3">Multimedia</td></tr>
<tr><td colspan="3">Rest of the vehicle</td></tr>
<tr><td rowspan="12">Engine related</td><td>Automotive battery (Pb)</td><td></td><td></td></tr>
<tr><td>Generator</td><td></td><td></td></tr>
<tr><td>Starter motor</td><td></td><td></td></tr>
<tr><td>Spark plug</td><td></td><td></td></tr>
<tr><td>Rocker cover gasket</td><td></td><td></td></tr>
<tr><td>Vee belt/Multi-groove belt</td><td></td><td></td></tr>
<tr><td>Timing belt</td><td></td><td></td></tr>
<tr><td>Air filter</td><td></td><td></td></tr>
<tr><td>Fuel filter</td><td></td><td></td></tr>
<tr><td>Muffler</td><td></td><td></td></tr>
<tr><td>Exhaust system</td><td></td><td></td></tr>
<tr><td>Engine oil</td><td></td><td></td></tr>
<tr><td rowspan="3">Added costs for braking</td><td>Brake fluid (extra cost)</td><td></td><td></td></tr>
<tr><td>Brake disk (extra cost)</td><td></td><td></td></tr>
<tr><td>Brake pad (extra cost)</td><td></td><td></td></tr>
<tr><td rowspan="3">Added costs for transmission</td><td>Gear oil (extra cost)</td><td></td><td></td></tr>
<tr><td>Transmission (extra cost)</td><td></td><td></td></tr>
<tr><td>Clutch (ICE-specific)</td><td></td><td></td></tr>
<tr><td rowspan="4">Power electronics</td><td></td><td colspan="2">PE: DC/DC</td></tr>
<tr><td></td><td colspan="2">PE: DC/AC</td></tr>
<tr><td></td><td colspan="2">Charger</td></tr>
<tr><td></td><td colspan="2">Traction e-motor</td></tr>
<tr><td>Battery related</td><td></td><td>Traction battery (Li-ion)</td><td></td></tr>
<tr><td rowspan="2">Fuel cell and battery related</td><td></td><td></td><td>Fuel cell</td></tr>
<tr><td></td><td></td><td>Traction battery (Li-ion)</td></tr>
<tr><td>H2 storage</td><td></td><td></td><td>H2 storage</td></tr>
</table>

## 3.5. Learning Curve Effect on New Technologies

It is natural to anticipate that the M&R costs for advanced novel technologies (BEVs and FCVs) will drop when such trucks are widely adopted in the market. According to the defined equation of M&R costs, the drop in the parts cost or the labor hours spent will drive a drop in the M&R costs as well. This study uses the learning curve theory to accommodate the declining cost trend associated with production quantity.

A learning curve effect means that, for each doubling of the cumulative production quantity, the unit cost will drop by a constant percentage (NASA, 2008). This can be expressed as follows:

$$C_n = C_1 \times n^{\log_2 b} ,$$

where

$n$ is the unit number (1 for the 1st unit, 2 for the 2nd unit, etc.),

$C_n$ is the cost to produce the *n*th unit,

$C_1$ is the cost to produce the 1st unit, and

$b$ is the learning percentage.

Estimates of the learning percentage generally fall in the range from 0.75 to 0.96, across numerous industries (Stewart et al., 1995). This study assumes a 12% learning curve cost reduction for each doubling, i.e., $b = 0.88$, which was also used in the European study (Propfe et al., 2012).

We assume that learning applies only to new technologies while considering current market status differences for different propulsion systems. The future technology market obviously corresponds to fully learned-out M&R costs and, to that end, BEVs and FCVs will have multiple rounds of learning which are assumed below.

For battery electric trucks, assume 3 times doubling to reach a fully learned-out cost level, corresponding to a cumulative cost reduction of 32%. This applies to the following cost component categories:

- power electronics: in both BEV and FCV cases.
- battery: in the BEV case.

For fuel cell trucks, assume 4 times doubling to reach a fully learned-out cost level, corresponding to a cumulative cost reduction of 40%. This applies to the following cost component categories:

- fuel cell and battery: in the FCV case.
- hydrogen storage: in the FCV case.

## 4. Results and Discussion

Based on the analytical methodology, assumptions, and exogenous input discussed earlier, we can derive the resulting M&R costs for advanced technology trucks. Both Figure 5 and Table 6 present the M&R cost breakdown and comparison across truck technologies, in 2020 dollars. Note that the midlife overhaul costs are not modeled or reported in the M&R cost results.

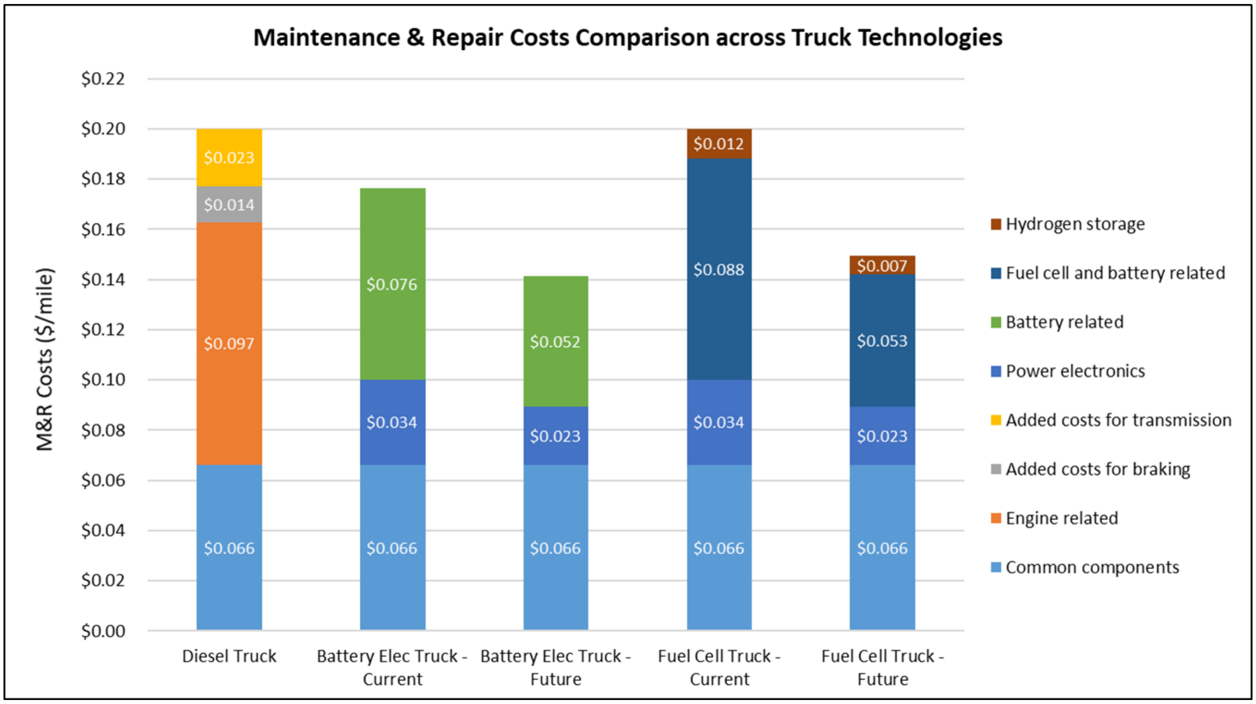


Figure 5. Heavy duty truck M&R cost breakdown and comparison across truck technologies

Table 6. Heavy duty truck M&R costs by cost component category (in 2020 $/mile)

| **Cost category** | **Diesel Truck** | **Battery Elec Truck - Current** | **Battery Elec Truck - Future** | **Fuel Cell Truck - Current** | **Fuel Cell Truck - Future** |
|---|---|---|---|---|---|
| Common components | $0.066 | $0.066 | $0.066 | $0.066 | $0.066 |
| Engine related | $0.097 | | | | |
| Added costs for braking | $0.014 | | | | |
| Added costs for transmission | $0.023 | | | | |
| Power electronics | | $0.034 | $0.023 | $0.034 | $0.023 |
| Battery related | | $0.076 | $0.052 | | |
| Fuel cell and battery related | | | | $0.088 | $0.053 |
| Hydrogen storage | | | | $0.012 | $0.007 |
| **Total M&R costs** | **$0.200** | **$0.176** | **$0.141** | **$0.200** | **$0.149** |
| **Cost reduction r.t. Diesel Truck** | | **-12%** | **-29%** | **0%** | **-25%** |

For benchmarking, the M&R costs for the reference HD diesel truck are also shown in Figure 5. Diesel trucks have overwhelmingly dominated the heavy duty market for many decades and, thus, their M&R costs are not expected to substantially change in the future. Note that the real-world cost data might show variations with year, just like the patterns demonstrated historically as in Figure 1 above. The diesel truck's overall M&R cost, $0.20/mile representing a historical average, works as an exogenous input, so varying its value can affect the results for battery electric and fuel cell trucks.

The cost breakdown by aggregated major components shows that, apparently, the diesel engine related costs play a major role and make up approximately half of the overall M&R cost. Compared to BEVs or FCVs, the diesel truck will incur extra M&R costs for its complicated transmission and braking systems. The estimated cost components are $0.023/mile for added costs for transmission and $0.014/mile for added costs for braking.

The common components category is estimated to incur $0.066/mile M&R costs and this cost number is assumed the same across powertrain technologies. This portion of M&R costs will also keep the same for current and future advanced technologies (BEVs and FCVs), as there is no significant learning effect being anticipated for the well-developed common processes or services. As a result, the common components cost will account for an increasing share of the overall M&R costs for the future years, in the BEV and FCV cases as their overall M&R costs will decline due to the learning effect.

On top of the common components category, the overall M&R cost for BEVs also includes contributions of battery and power electronics, as shown in Figure 4. For current BEV trucks, the battery M&R cost of $0.076/mile is based on a value for light duty vehicles and then scaled for HD trucks. So is the power electronics M&R cost of $0.034/mile. In an anticipated mature market, the future truck M&R costs associated with battery and power electronics are expected to drop to $0.052/mile and $0.023/mile, respectively, indicating that the learning curve effect will cause a 32% reduction compared to the current cost levels. Note that the overall M&R cost for the whole truck will correspond to a cost reduction less than 32% as there is no learning effect for the traditional common components.

Similarly, for current FCV trucks, their component-level M&R costs are also derived from scaling the values for light duty vehicles. The M&R costs for future FCV trucks are a result of the current costs (at the aggregated component level) adjusted by the learning curve effect. For the fuel cell system and hydrogen storage, the learning curve effect will cause a 40% reduction compared to the current cost levels. The power electronics cost will be the same as for BEVs, a 32% cost reduction. The particular component-level results are shown in Figure 5 and Table 6.

From the whole vehicle perspective, the current BEVs have an overall M&R cost of $0.176/mile, approximately 12% lower than their diesel counterpart. Due to the learning curve effect in a BEV growing market, the future BEVs will have more pronounced maintenance benefits and only incur a $0.141/mile M&R cost, 29% lower than the reference diesel truck.

The current FCVs happen to have M&R costs roughly equivalent to their diesel counterpart. Like BEVs, due to the learning curve effect, the future FCVs will have less maintenance needs and cause a $0.149/mile M&R cost, 25% lower than the reference diesel truck. Within our analytical framework, the overall M&R cost for the BEVs will always be slightly lower than for the FCVs as hydrogen storage will contribute some additional M&R costs in the FCV case.

Moreover, Figure 5 clearly indicates that M&R costs for HD trucks tend to be driven by the propulsion system (such as the engine, the traction battery, or the fuel cell system), which accounts for a significant share of the overall M&R costs.

Taking this a step further, the developed method and results can be easily generalized to other vehicle applications where feasible, despite that the study is carried out by examining the case of heavy duty long-haul trucks. For example, it is reasonable to assume that the M&R cost numbers developed in this study can apply to medium duty single-unit trucks as the current M&R cost values for the medium duty reference diesel truck are roughly the same as for the long-haul trucks (Burnham, 2020).

# 5. Summary and Conclusions

Currently there is very limited data on M&R costs for advanced heavy duty technologies such as battery and fuel cell trucks. In this study, we developed an analytical method to estimate M&R costs at the aggregate component level for battery electric and fuel cell heavy duty trucks, by taking advantage of the existing literature and data on heavy duty diesel trucks and passenger cars.

The M&R costs for advanced technologies are linked to the reference diesel truck data, using an exploratory analytical method which aims to extend the diesel truck results to novel technologies, such as battery electric and fuel cell trucks. By analogy, the developed method can also be applied to other vehicle applications where feasible. Results indicate that M&R costs for advanced technologies are expected to drop significantly due to the learning curve effect. Compared to the diesel truck, future battery electric trucks will have 29% less M&R costs and future fuel cell trucks will have 25% less.

Note that these analytical cost results could be different from future real-world observations, but the linking-to-diesel method makes them stay in a reasonable range, assuming the diesel truck cost data is reliable and representative. Moreover, the developed M&R cost values reflect the current understanding in today’s diesel-dominant truck world, and also fill in the gap for conducting a complete TCO analysis in which maintenance costs are an integral component, but often left out, due to the lack of data for full electric heavy duty trucks (BEVs and FCVs).

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