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# Driving an Industry: Medium and Heavy Duty Fuel Cell Electric Truck Component Sizing

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**Summary**

Medium and heavy duty (MD and HD respectively) vehicles are responsible for 26 percent of the total U.S. transportation petroleum consumption [1]. Hydrogen fuel cells have demonstrated value as part of a portfolio of strategies for reducing petroleum use and emissions from MD and HD vehicles [2] [3], but their performance and range capabilities, and associated component sizing remain less clear when compared to other powertrains. This paper examines the suitability of converting a representative sample of MD and HD diesel trucks into Fuel Cell Electric Trucks (FCETs), while ensuring the same truck performance, in terms of range, payload, acceleration, speed, gradeability and fuel economy.

*Keywords: fuel cell, hydrogen, truck, simulation, HEV*

## 1 Introduction

The large number of truck body types, weight classes, and vocational uses in the MD/HD commercial vehicle market results in a large potential FCET design space. Coupled with this wide range of possible vehicle configurations and applications, each class/vocation has unique functional requirements that define specific vehicle system design choices. To capture the full breadth of the MD/HD market, candidate truck classes and vocations were identified by their recent market size using the Vehicle Inventory and Use Survey (VIUS) [4]. The list of vehicles chosen in this study spans nearly all weight classes and many common vocations, and is shown in Table 1. Baseline trucks were picked for each candidate class and vocation based on market share. Some of these choices span multiple weight classes and are popular in multiple vocations. As such, manufacturers design these trucks with requirements suitable for a variety of use cases. When such trucks are converted to FCETs, it is important to ensure that functional capabilities are not sacrificed.

Table 1. Overview of the weight classes and vocations considered in this study.

| Vehicle Class | Vocation/ Description |
|---|---|
| class 2b, 6000 – 10000 lbs | Small Van |
| class 3, 10001 – 14000 lbs | Enclosed Van |
| class 3, 10001 – 14000 lbs | School Bus |
| class 3, 10001 – 14000 lbs | Service, Utility Truck |
| class 4, 14001 – 16000 lbs | Walk In, Multi Stop, Step Van |
| class 5, 16001 – 19500 lbs | Utility, Tow Truck |
| class 6, 19501 – 26000 lbs | Construction, Dump Truck |
| class 7, 26001 – 33000 lbs | School Bus |
| class 8, 33001 lbs or heavier | Construction, Dump Truck |
| class 8, 33001 lbs or heavier | Line haul |
| class 8, 33001 lbs or heavier | Refuse, Garbage Pickup, Cab over |
| class 8, 33001 lbs or heavier | Tractor Trailer |

## 2 Baseline vehicle benchmarking

While it is not easy to verify every functional requirement considered by the various manufacturers, it is possible to calculate important fundamental capabilities of a vehicle that are directly related to its powertrain. This is done through benchmarking the baseline vehicle model. The parameters characterizing vehicle performance for this process are 0-30 mph acceleration time, 0-60 mph acceleration time, maximum sustainable speed at 6% grade, and cruising speed at highway conditions. The baseline trucks were modelled based on the data available from manufacturers as well as third parties [5]. Autonomie was used as the tool for this simulation analysis, as it has various library models that have already been validated [6] [7] [8] [9].

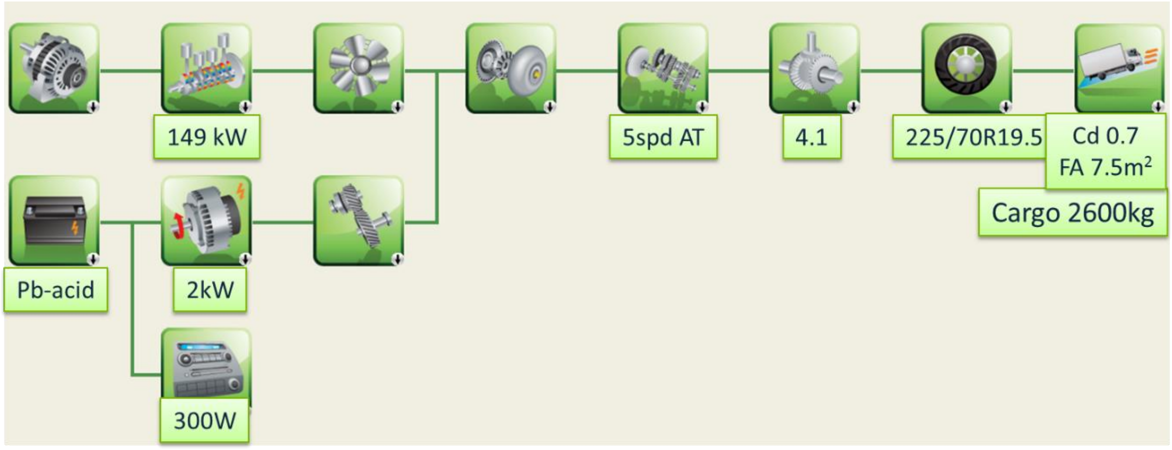


Figure 1. Schematic diagram for a conventional medium duty vehicle. Component specifications are also shown.

Figure 1 represents the vehicle, as modelled in Autonomie. Automatic or manual transmission model can be used, based on what is used in the baseline vehicle. Final drive ratios, tire sizes and vehicle weight are also set based on the baseline vehicle. Auxiliary electric load is assumed to be an average of 300W over the entire duration of the cycle. This is an approximation for loads that might come from electronic controller units, air conditioner, fans and lights used in the vehicle. Mechanical auxiliary loads are accounted for in the engine efficiency data; hence no additional mechanical load is considered.

Modelling and simulation was done for all vehicle classes shown in Table 1, but to demonstrate the design and simulation process, this paper focuses on a Class 4 delivery van as an example. Benchmark values for the baseline model are shown in Table 2. The goal of the FCET sizing process is to ensure that the fuel cell powered vehicle can match or better these performance criteria.

Table 2. Benchmark values for the Class 4 delivery van

| Performance Criteria | Baseline |
|---|---|
| Cargo Mass (lb) | 5280 |
| Cruising Speed (mph) | 70 |
| Grade Speed (mph) | 50 |
| 0-30 mph acceleration time (s) | 7.2 |
| 0-60 mph acceleration time (s) | 29.8 |

## 2.1 Test weight

All of the baseline vehicles are simulated and benchmarked at the median gross vehicle weight rating (GVWR) value of its weight class. GVWR for a class 4 truck is between 14000 and 16000 lbs. To make the test representative of all possible vehicles in that class, a test weight of 15000 lb is used. The baseline vehicle models are built to match the curb weight of the truck. Simulated cargo mass is then added to bring the test weight of the truck to the median load for its weight class. In our example, this would mean a cargo of 5280 lb on a Class 4 delivery van. This weight may not reflect the typical operational weight for all vocations, but this assumption is used to represent the median of the weight class definition and is in line with SAE J1321 test procedures for on-road testing of fuel consumption [10].

## 2.2 Cargo mass

When the conversion from a baseline vehicle to an FCET is done, the curb weight of the truck will change based on components being added and removed, but the cargo mass of the baseline vehicle is kept the same to ensure the FCET has at least comparable performance capability to the baseline vehicle when loaded with the same amount of cargo. The cargo space also remains uncompromised. More detail on the mass descriptions and comparison can be found in section 3.1.2.

## 2.3 Acceleration, Cruise & Grade

The various categories of performance are explained in the following subsections. The baseline conventional vehicle model for each class is simulated to obtain benchmarking data. These tests reveal several aspects of the truck's capabilities. Continuous performance capabilities will be tested in the grade and cruise tests. Peak power output as well as gear ratios will determine the acceleration performance. FCETs are sized to meet or exceed their respective baseline vehicles in these four tests.

### 2.3.1 0-30 mph acceleration time

This calculates the time taken for the vehicle to achieve a speed of 30 mph from a stop. The conventional vehicle will mostly run the lower gears during this test. The FCET model in this study includes a single speed gearbox, and will have to rely on the motor and overall fixed gear ratio to meet the speed and torque demand. The peak power of the motor and its ability to drive at high power output conditions for a few seconds is important in this test. Both the battery pack and fuel cell can provide the power during this test.

### 2.3.2 0-60 mph acceleration time

This calculates the time taken for the vehicle to achieve a speed of 60 mph from a stop. The conventional vehicle will rely on the peak engine power and gear ratios that help keep the engine in the appropriate speed range during this test. For the FCETs, unlike the 0-30 mph acceleration test, the motor has to sustain high power for 20-30 seconds. Both the battery pack and fuel cell can provide the power during this simulation.

### 2.3.3 Sustainable maximum speed over an 11-mile run at 6% grade

This is an approximation for the 'Davis Dam test', one of the toughest road grade conditions in the U.S. [11]. We assume that the conventional vehicles can produce constant power output from their engine. The electric motor in the FCET will be controlled at the constant operating power range during this test. This keeps the motor from overheating. The battery pack will run out of energy in this case so the fuel cell will have to provide the continuous power required during this simulation.

### 2.3.4 Cruising speed

Minimum cruising speeds were set for each class based on the use cases. Vehicles that belong to the weight classes 1-4 were expected to be capable of cruising at 70 mph, and higher class vehicles were expected to sustain at least 60 mph on a highway driving scenario. While this is an easy test for the conventional vehicles, the electric motor in the FCET will be controlled at the constant operating power range during this test. The highest overall gear ratio applicable for the FCET is determined based on this test. The battery pack will run out of energy in this case so the fuel cell will have to provide the continuous power required during this test.

# 3 FCET Sizing Methodology

The FCET considered in this study is a hybrid vehicle which uses a fuel cell as the primary source of energy. The battery is used for assisting the fuel cell during high power transient operations and for regenerative braking. The schematic diagram for the FCET powertrain is shown in Figure 2. The major components that are being sized in this study include the motor, battery, fuel cell and the overall gear ratio. Several assumptions have to be made in order to size these components. Those assumptions are explained below.

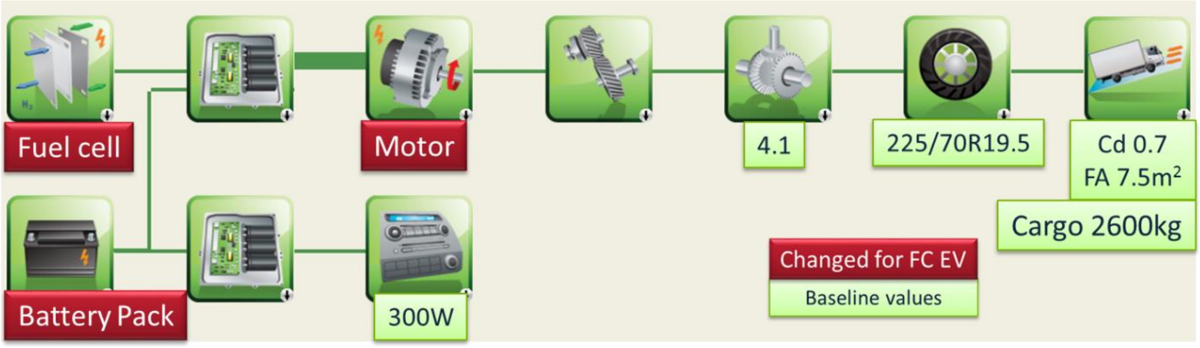


Figure 2. Schematic diagram for a medium duty fuel cell electric truck.

## 3.1 Assumptions

Component sizes are not always dependent on specific component technologies. For example, a motor with a 100 kW continuous power rating should provide that level of rated power whether it is an AC induction machine or DC series motor. However, in order to ensure the commercial feasibility of the chosen components, technologies that are commercially available are utilized.

The motor used in this study is a brushless permanent magnet synchronous machine. [12]. For this study, the efficiency map of a commercially available 145-kW motor was selected in Autonomie, and the power was scaled to simulate a motor with similar efficiency characteristics.

The battery is assumed to use li-ion technology. Battery cell data is based on manufacturer supplied publicly available information [13].

For fuel cells, the energy and power density is based on the estimates made by experts within the U.S. Department of Energy's programs [14]. 400 W/kg & 400 W/liter are assumed to be the power density and specific power of commercially available automotive fuel cells.

### 3.1.1 Components added and removed

In this study we assume that a fuel cell conversion of the baseline vehicle precludes any change of the vehicle chassis or body. Powertrain components such as the engine and fuel tank will be replaced with a motor, fuel cell and hydrogen storage tanks. Certain components including the gearbox and torque converter can be removed since they are not necessary for a fuel cell drivetrain. The final drive ratio will have to change to accommodate the higher range of motor speeds. It is assumed that either the new components will consume the same volume as the ones they are replacing, or additional space is available on the trucks to accommodate larger components like the hydrogen storage tank. This is explained later in the section about hydrogen storage feasibility.

### 3.1.2 Mass, power & energy density assumptions

For the component sizing, it is important to consider the difference in mass for fuel cell conversion. The estimated mass of each component is shown in the table below. The mass of engine, transmission, motor & battery are based on data available from vehicle manufacturers and tier 1 suppliers [15] [16] [17] [18] [19].

The weight of these components have a correlation with their performance characteristics such as torque, and this was used to estimate the component mass for this study.

Table 3. Mass difference between Baseline vehicle and its FCET version

| Mass estimates in kg | Baseline | FCHEV |
|---|---|---|
| Test weight | 6809 | 6854 |
| Chassis + Body | 3417 | 3417 |
| Cargo | 2400 | 2400 |
| Fuel | 100 | 19 |
| Fuel tank | 40 | 435 |
| Engine | 305 | |
| Fuel cell | | 125 |
| Gearbox | 142 | 10 |
| Motor | | 145 |
| Battery Low Voltage | 83 | 83 |
| Battery High Voltage | | 65 |

It should be noted that the low voltage battery in the conventional vehicle is retained in the FCET architecture. The high voltage battery is added which results in an increase to the mass of the total battery system.

## 3.2 Continuous & Peak Power requirements

In general, the electric machines have a continuous rated power and are capable of producing about twice as much power for short durations. During such high power operation, their temperature increases and a controller brings down the output to continuous, sustainable levels for safe operation.

Propulsion power requirements during acceleration tests last for less than 20-30 seconds, and the motor may be operated at levels above its continuous operating range. The electrical power can come from a combination of battery and fuel cell for these tests.

Tests that run for longer duration, like cruise and grade tests, have to be met with fuel cell power alone. The motor too should be able to remain within its continuous operating range as shown in Figure 5.

## 3.3 Motor sizing

Motor size is determined to ensure that it can meet the peak and continuous power requirements within a tolerance of +/-2 %. These power requirements are estimated by simulating the FCET Autonomie model over all the benchmarking tests. The acceleration test results are shown in Figure 3 and the grade and cruise test results are in Figure 4.

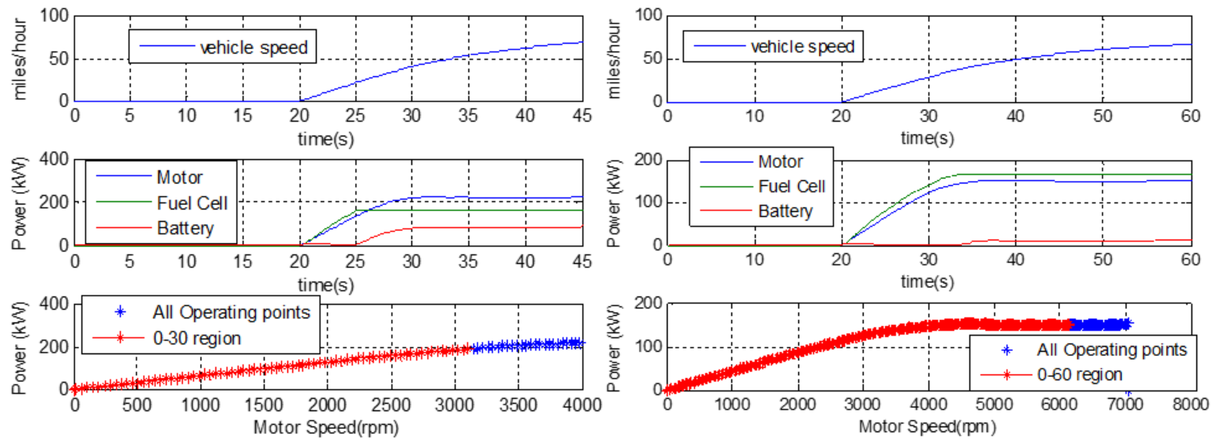


Figure 3. Acceleration power requirement of motor is estimated at 224 kW for the FCET to achieve 0-30 mph in 7.2 s (left) and 154 kW motor output power is sufficient for accelerating from 0-60 mph in 29.8 s (right).

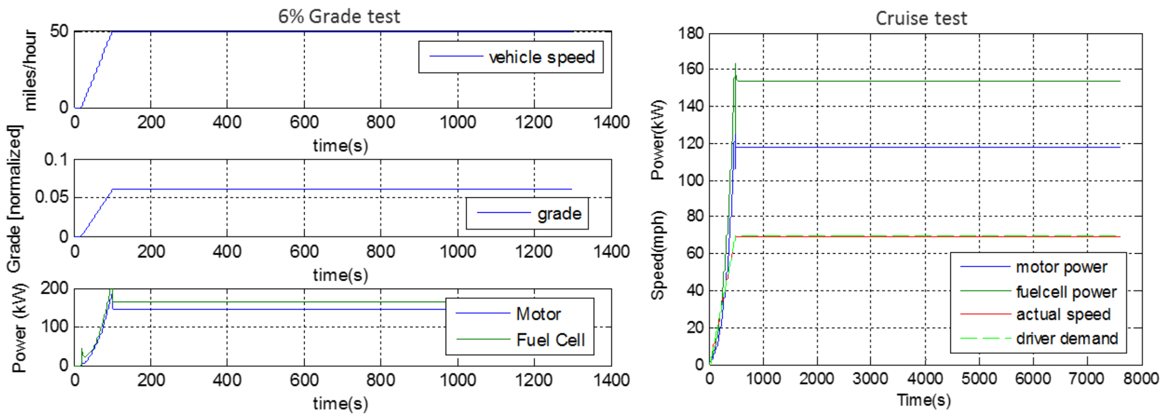


Figure 4. Power requirement for 6% grade at 50 mph and 70 mph cruise. 144 kW is required for the grade test and 118 kW for cruise test.

This sizing logic is used to estimate the power required for each of these tests, and can pick a suitable overall ratio needed to accomplish the test.

Table 4. Peak and continuous power requirements for each test

| Parameters | Grade | Cruise | 0-30 | 0-60 |
|---|---|---|---|---|
| Motor Power Required (kW) | 144 | 118 | - | - |
| Motor Peak Power Rating (kW) | - | - | 224 | 152 |
| Fuel Cell Power (kW) | 164 | 154 | - | - |
| Battery Power (kW) @60% SOC | - | - | 54 | 9 |
| Usable Battery Energy (Wh) | - | - | 29 | 47 |
| Total Battery Energy (Wh) | - | - | - | 233 |

These power requirements are sufficient to meet each test, but the higher speed-reduction ratio used for a grade test might prevent the vehicle from reaching its higher cruise speed requirements. Since this study only explores and models a fuel cell electric truck with just a single speed transmission, it is necessary to find the lowest motor power and the final drive ratio which will satisfy all of these conditions.

Figure 5 is used to depict the selection process for the final drive ratio. As the final drive ratio changes the motor speed changes, but it should still produce the same desired power to meet each requirement (shown by red dots in increments of 0.1). If all four operational power requirements cannot be satisfied by varying the final drive ratio, then motor power is increased. Motor power scaling is shown in increments of 10 kW by several lines (green and magenta) indicating the operating region of the motor for peak (30 s) and continuous operation. A final drive ratio is selected to meet all the power requirements simultaneously while minimizing the motor's power requirements. This search provides us the lowest motor power and the overall drive ratio which would satisfy all the performance requirements. The result from this process is shown in Figure 5.

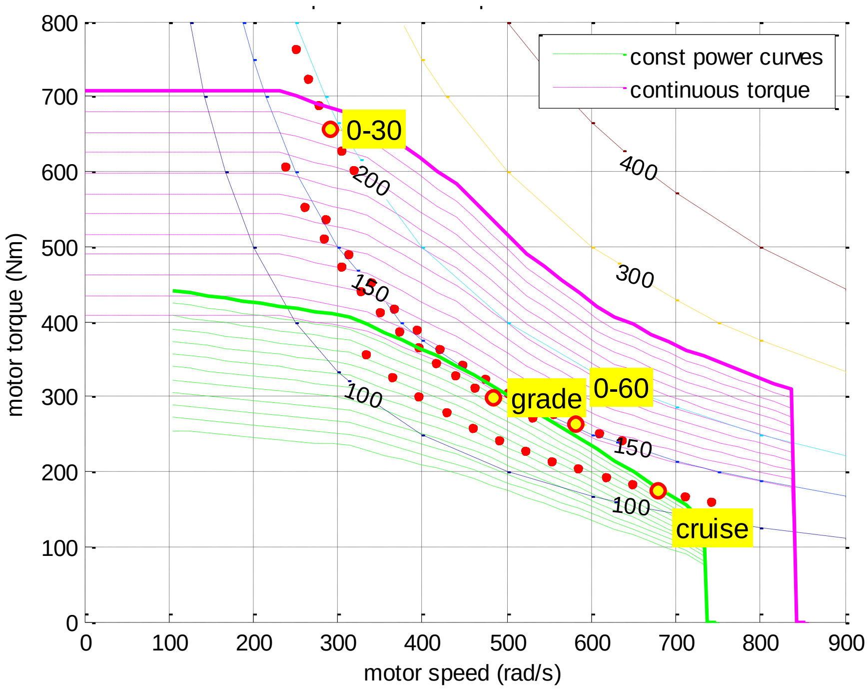


Figure 5. Finding an appropriate motor power and the overall speed reduction ratio.

Power required for the acceleration tests are within the peak power output. Grade and cruise power requirements fall just under the continuous operating range of the motor. A finer step size in incrementing motor power and final drive ratio can cause about a 5% difference in the overall motor sizing. The next smaller motor considered in this sizing could not meet those two criteria at their respective required operating speeds. This sizing logic holds good for single-speed powertrains. If a two speed gearbox is introduced, it allows the motor to meet the cruising power requirements at a lower speed. That might help in further downsizing the motor at the expense of a more complex transmission, however multi speed transmissions are not considered in this study. Table 5 shows the results obtained after varying final drive ratio and the motor power.

The results shown in Table 4 are not specific to a particular electric machine or a given transmission ratio; however the numbers in Table 5 depend on the discrete motor sizes and ratio chosen. Table 5 also depends on the specific motor we consider for this study. For example, it depends on the exact shape of the peak torque and continuous torque curves of the motor. It can be seen in Figure 5, that the overall ratio is adjusted such that the cruising point and grade operation point are both very close to the continuous operating limit of the motor. The motor can output 151 kW at 500 rad/s which satisfies the grade requirement. At close to 700 rad/s it can only provide 120 kW, but that is enough for the maximum continuous cruising speed requirement. If the shape of the continuous torque output curve was different, the logic might yield a different motor rating and over all ratio.

Table 5. Results of the motor power and final drive sweep test

| **Selected component sizes** | |
|---|---|
| Motor Continuous Power (kW) | 151 |
| Motor Rated Power (kW) | 260 |
| Fuel Cell Power (kW) | 164 |
| Battery Power (kW) | 54 |
| Battery Total Energy (Wh) | 1426 |
| Battery Volume (L) | 53.4 |
| Motor Speed Ratio | 8.9 |

## 3.4 Fuel cell sizing

The fuel cell is sized to meet the maximum continuous power requirement. In this case, the maximum continuous power requirement at the motor is 144 kW. While accounting for the losses at various components, we see that the total electrical load on the fuel cell is 164 kW.

## 3.5 Battery sizing

Battery power should be adequate to augment the fuel cell power to meet peak input power requirements during the motor acceleration tests. The battery should also store enough energy to sustain this power output through the duration of the acceleration test. Typically, we see that the power is decided by the 0-30 mph test, and the battery energy is determined by the longer 0-60 mph acceleration test. As it is seen in most hybrid vehicles, it is assumed that only about a 20% SOC swing is allowed for the battery. This results in a pack that can provide 54 kW power and a total energy of 233 Wh (47 Wh usable). Since the fuel cell is already sized for climbing 6% grades at highway speeds, it is capable of providing similar power output as the IC engine in the baseline vehicle. This ensures that the energy drawn from the battery is quite small. It is to be noted that this energy is sufficient for only a few seconds operation during one acceleration event.

This battery size is similar to that of light duty hybrid vehicles (~50kW, ~1 kWh). The battery size is not optimized for fuel economy in this case. If we account for the need to capture all the regenerative braking energy, then a larger pack might be warranted.

## 3.6 Overall gear ratio

The motor operation at the low speeds is subjected to torque limits imposed by the motor controller and is relatively inefficient at these speeds. Varying the gear ratio at the differential allows for motor operation at higher speeds, higher efficiency, and higher power regions. A speed reduction ratio that is too high might prevent the vehicle from achieving its maximum speed requirement. The ideal ratio should cover all the operating conditions shown in Figure 5 with the minimum power rating of the motor. In this case an overall ratio of 8.9 is shown to satisfy all the performance criteria.

## 3.7 Estimating Fuel Economy

EPA's proposed test procedure for MD & HD vehicles is used to estimate fuel economy. The drive cycles used in EPA's test method represent extreme operating conditions for these vehicles. To account for the worst case scenario, the worst fuel economy observed for the FCET in ARB transient, Mild 55 & Mild 65 cycles is used to size the hydrogen storage requirements to meet vehicle range.

Table 6. Simulated Fuel Economy Comparison

| **Fuel economy** | **Baseline (mpg)** | **FCET (mpkg)** |
|---|---|---|
| ARB Transient | 17 | 30.4 |
| Mild 55 | 12.4 | 14.2 |
| Mild 65 | 9.6 | 10.4 |
| **Weighted Vocational Fuel economy** | | |
| Regional | 14.1 | 21.5 |
| Multi use | 16.1 | 27.4 |
| Urban | 16.7 | 29.4 |

### 3.7.1 Real world cycles from NREL

In addition to the regulatory cycles, the functional usefulness of the FCET is measured using real world drive cycles stored in NREL's FleetDNA database [20]. This data has been collected from 41 unique vehicles operating in multiple fleet locations across the United States, and is representative of real world vehicle operation over a total of 563 daily drive cycles. For the class 4 delivery vans, the real world fuel economy varied between 10 miles/kg to about 18 miles/kg. As shown in Figure 6, an on board hydrogen storage of 12 kg satisfies all the use cases sampled from FleetDNA. The red line shows the cumulative fraction of the cycles that falls under a given x-axis value for distance or stored hydrogen. This can be used to estimate how much hydrogen is required to satisfy a percentage of trips (i.e. 7 kg can satisfy 90% of trips).

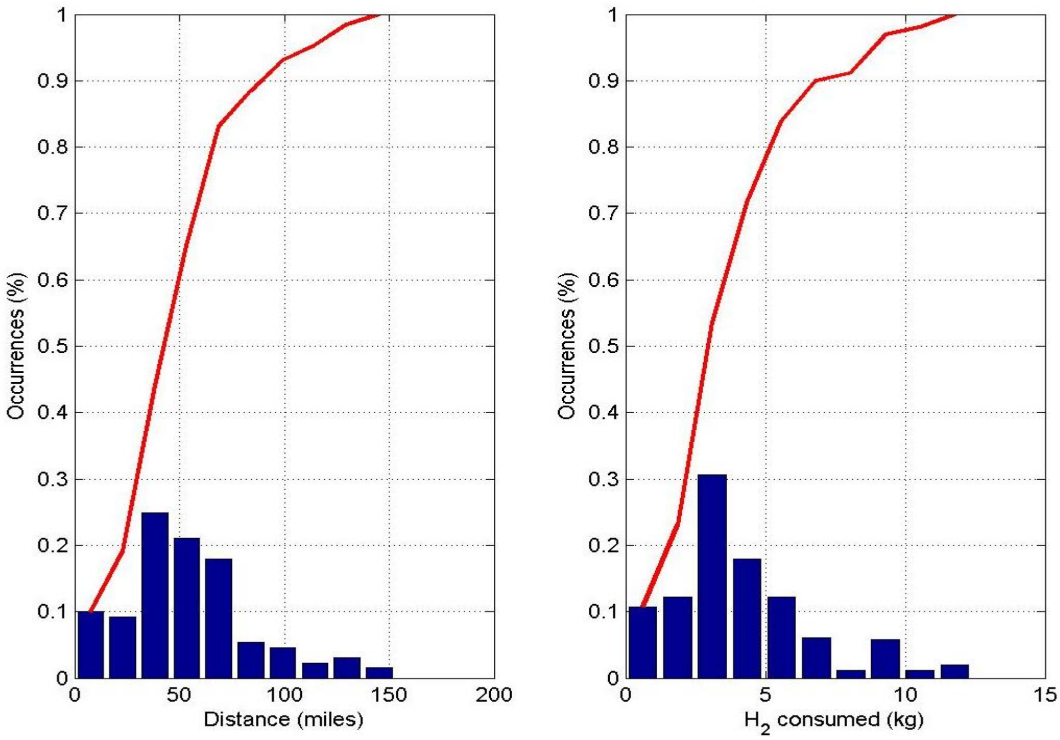


Figure 6. Performance of the Class 4 FCET on cycles from FleetDNA database. 150 mile range and 12 kg of Hydrogen is needed to satisfy all the driving conditions considered.

## 3.8 Onboard Hydrogen Storage

Onboard hydrogen storage requirement estimates vary with range. It is important to check how much storage is possible within the specific vehicle. Assuming various tank dimensions and storage pressure, we can come up with two designs. The 'Fleet design' allows storing enough hydrogen to cover the fleet range estimated in the VIUS surveys. This would also cover the distance observed in the FleetDNA database. The 'Max design' is for a maximum possible storage considering one of the longest available wheelbases available in this class of vehicles. Longer wheelbase provides more volume for the hydrogen tanks mounted on the side rails of the chassis. These results are shown in Table 7.

Table 7. Examining the volume available for on-board hydrogen storage

| **H2 Storage Parameters** | **"Fleet" Design** | **"Max" Design** |
|---|---|---|
| Tank Location/# of Tanks | Side Rail/2 | Side Rail/2 |
| Tank Pressure (bar) | 350 | 350 |
| Tank Diameter (in) | 19.6 | 19.6 |
| Tank Length (in) | 93.5 | 119.1 |
| Total Tank Mass (kg) | 272.6 | 334.4 |
| Total H2 Storage (kg) | 19.23 | 24.19 |
| Gravimetric Weight % | 6.6 | 6.93 |
| Wheelbase (in) | 190 | 208 |

# 4 FCET Sizing Results

The FCET component specification that was sized using the methodology described in this study met all the vehicle requirements within the desired tolerance of 2%. As shown in Table 8, it is able to carry the same cargo, meet the grade and cruise performance of the baseline vehicle, and significantly exceed the acceleration performance requirements.

Table 8. Comparison of FCET performance against baseline

| Performance Criteria | Baseline | FCET |
|---|---|---|
| Cargo Mass (lb) | 5280 | 5280 |
| Cruising Speed (mph) | 70 | 69 |
| Grade Speed (mph) | 50 | 50 |
| 0-30mph acceleration time (s) | 7.2 | 6.8 |
| 0-60mph acceleration time (s) | 29.8 | 22.2 |

# 5 Summary

This paper puts forth a preliminary process to estimate component sizes of a fuel cell powered electric truck to meet the functional requirements of a reference baseline vehicle. It accounts for the mass difference due to component changes, and the feasibility of finding the necessary volume for the hydrogen tanks. Although this paper used a Class 4 truck as an example, similar analysis was done for a broader range of weight classes and vocations. This shows that there are no major technological hurdles to meet performance requirement for trucks with hydrogen and fuel cell systems. Cost and durability have not been considered, but may present challenges until markets are established and economies of scale reduce the cost of producing fuel cell systems. The vehicle use cases were checked against national surveys as well as data collected from major fleet operators. The next step will be to add the ownership cost component into this study to examine the economic feasibility of these vehicles.

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