June 2020

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NACFE
NORTH AMERICAN COUNCIL FOR FREIGHT EFFICIENCY

INFORMATIONAL

Fuel Cell
Electric Trucks

An analysis of hybrid vehicle specifications for regional freight transport

Data provided by the North American Council for Freight Efficiency. Analysis conducted by Ballard Power Systems.

Contents

Executive Summary

Government, fleet users, logistics companies, and consumers are moving aggressively toward zero-emission mobility. There's an accelerating shift toward cleaner and cost effective solutions in the medium- and heavy-duty motive markets.

Almost every vehicle manufacturer and supplier to the trucking industry is actively investing in low-emission and zero-emission powertrains. And fleet operators are assessing the technology options to meet increasingly stringent emissions reduction regulations. It is imperative that truck manufacturers and operators understand the duty cycles and use cases where each power source offers the strongest value proposition.

To that end, Ballard Power Systems has undertaken an in-depth analysis of real-world operational data provided by the North American Council for Freight Efficiency (NACFE). Employing NACFE's Run on Less data sets, Ballard analyzed regional haul truck duty cycles with the objective of recommending comparable fuel cell – battery electric (hybrid) powertrain solutions. Simulations of these fuel cell trucks operating over the duty cycles were completed, fuel cell and battery operational parameters reported, and fuel consumption estimated.

Results show that the majority of duty cycles could be met with a 200kW fuel cell and battery packs of 32kWh or lower capacity. Only a small reduction in payload carrying capacity is required and refueling times are estimated at less than 25 minutes, thereby enabling high utilization zero-emission freight movement.

For the freight industry, our study confirms that fuel cell electric powertrains offer four key advantages over a pure battery powertrain: longer range, greater power, more payload capability, and faster refueling leading to high utilization of the truck asset.

Although fuel cell electric vehicles are currently more expensive to operate than battery electric and internal combustion commercial vehicles, they are set to become much lower cost as manufacturing technology matures, economies of scale improve, hydrogen fuel costs decline, and infrastructure develops. Based on real cost data from the hydrogen and fuel cell industry, expert analysis shows that fuel cell electric vehicles can be the lowest cost solution, beating both other low-carbon and fossil-based solutions for certain commercial applications like heavy-duty transport.[i]

Introduction

It seems like an impossible contradiction: for the sake of the planet, greenhouse gas emissions (GHG) from vehicles must go down significantly. And yet, with global trade and e-commerce thriving, truck transportation hauls a majority of America's freight tonnage.[ii] By 2040, the US Department of Transportation predicts that freight volume in the United States will grow by 29 billion tons. This is an astounding 45% percent increase that will cause congestion on our highways, intensify local air pollution and contribute to emissions.[iii]

The increase in freight traffic is about to meet environmental pressures (and government legislation) head on. Truck fleet operators don't have to look very far into the future to see that drastic change is on the way. California has a plan to have 100% zero-emission truck sales by 2040, with sales requirements for the heaviest trucks beginning in 2024 and gradually increasing until 2030. Other states are considering following suit.

Almost every vehicle manufacturer and supplier to the trucking industry is actively investing in low-emission and zero-emission powertrains. There are many options when it comes to alternative power sources, including:

- natural gas
- biodiesel
- battery electric
- hydrogen fuel cells

Research is underway to understand the duty cycles and use cases where each power source offers the strongest value proposition.

RUN ON LESS BY NACFE

A joint effort between the North American Council for Freight Efficiency (NACFE) and Rocky Mountain Institute, Run on Less is a best-of-the-best, cross-country roadshow that showcases advancements in freight efficiency. The goal of the Run is to highlight the best possible current use of the efficiency technologies, operational practices, and driver capabilities to show what the most innovative fleets can accomplish in the real world in terms of fuel economy and freight efficiency. Run on Less showcases how efficiency technologies improve the bottom line for fleets and benefit the environment by reducing greenhouse gas emissions.

Study Objective

In the fall of 2019, data loggers were installed on 10 heavy-duty trucks to collect real world Class 8 regional haul duty cycle data over a three week period in October 2019. These 10 trucks accumulated 58,633 miles (94,569km) in a variety of US locations as part of the North American Council for Freight Efficiency (NACFE) Run on Less Regional (RoLR) demonstration of the effectiveness of current production diesel and natural gas tractor technologies in the hands of well-trained drivers.

The data loggers were configured in concert with the U.S. National Renewable Energy Laboratory (NREL) working with Oakridge National Laboratory (ORNL). Furthermore, the use of GEOTAB and LinkeDrive fleet tracking and management systems enabled additional data points to be logged.

Employing NACFE's RoLR data sets, Ballard provided analysis of eight of the 10 regional haul vehicle duty cycles with the objective of recommending comparable fuel cell – battery electric (hybrid) vehicle specifications specific to these duty cycles. The process is outlined in Figure 1.

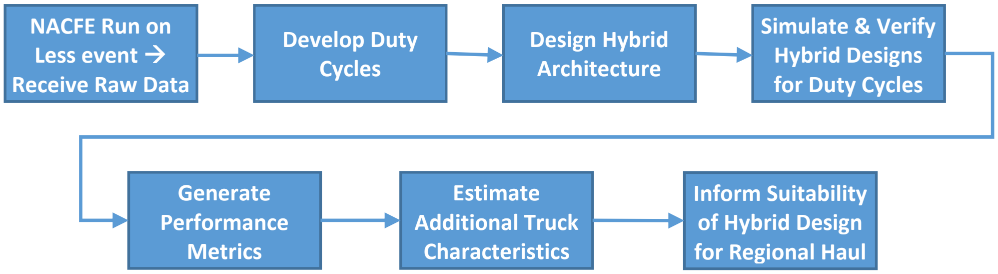


Figure 1: High level process description

The goal is to provide factual comparisons in an unbiased manner to address a range of factors previously identified by NACFE in published reports as relevant to promoting both fuel cell and battery electric Class 7 and 8 tractors as viable candidates versus diesel and CNG tractors. The results of this study will also be used to characterize potential regional operations where these vehicles offer the best value.

Data Mining

The Ballard team evaluated over 1,300 data files totaling nearly 100GB of data from the 2019 NACFE RoLR event. A process was developed to sort through the files to identify valid data. Data records with missing data points were ignored; this eliminated two of the 10 vehicles. Data files with “clean” date-time stamps were assembled, and four data points were extracted from each file:

- Engine torque percent at 1Hz frequency
- Nominal friction percent at 1Hz frequency
- Engine revolutions per minute (RPM) at 1Hz frequency
- Vehicle ground speed at 1Hz frequency

These steps reduced the number of files to one data file for each vehicle for each day where there was valid data.

The objective of this effort was to mine data which could be used to calculate approximate engine power delivered to the vehicle drive train for each of the vehicles for each day of the RoLR event. Additionally, ground speed is needed for calculating distance traveled and, ultimately, estimating fuel consumption per distance for the proposed hybrid architectures. Table 1 indicates the data set available for this effort; distance traveled is shown for each vehicle and day, and days with no valid data or distance < 10km (6 miles) are grayed-out. In summary, there were 108 truck days of data analyzed in this study.

Table 1: NACFE RUN ON LESS REGIONAL[iv], Fleet daily mileage, km

Date	Truck 1	Truck 2	Truck 4	Truck 5	Truck 6	Truck 7	Truck 8	Truck 10
4-Oct-19	0	0	0	0	0	0	0	6
5-Oct-19	0	8	0	0	0	0	0	0
6-Oct-19	1	823	0	0	0	0	0	0
7-Oct-19	650	678	842	914	642	225	0	872
8-Oct-19	1321	749	0	889	622	777	567	873
9-Oct-19	1259	437	561	601	646	745	553	837
10-Oct-19	1262	769	855	775	655	813	656	873
11-Oct-19	695	537	962	1028	666	711	726	872
12-Oct-19	683	0	0	928	0	0	628	0
13-Oct-19	0	770	0	0	0	0	0	2
14-Oct-19	596	804	561	303	660	269	349	836
15-Oct-19	671	570	816	855	628	808	633	873
16-Oct-19	697	677	664	827	659	847	811	837
17-Oct-19	663	734	836	233	626	780	668	833
18-Oct-19	643	607	598	878	420	699	729	944
19-Oct-19	698	0	0	160	0	0	809	0
20-Oct-19	0	620	0	0	0	0	1	2
21-Oct-19	0	796	0	324	0	0	1	876
22-Oct-19	700	695	0	930	0	0	623	875
23-Oct-19	701	311	0	1152	0	0	599	874
24-Oct-19	678	557	0	127	0	0	0	875
25-Oct-19	1254	538	0	217	0	0	0	801

Note: Thee official Run on Less Regional event ran from October 7 to October 23

Using the engine torque – and assuming a flat torque curve – for each vehicle, data in these clean files was used to convert engine torque and RPM to engine power using the formula:

> Engine Power, kW = (engine torque % - nominal friction %) / 100 × reference torque × engine rpm × (1/60) x (2π) / 1000

Using engine torque and friction values in the calculation for Engine Power introduces both +/- error, but the data sets are large and the errors tend to balance.

Finally, the calculated engine power and ground speed versus time were saved as duty cycle files. Note that the calculated engine power is a higher value than traction power because engine power additionally accounts for auxiliary loads and losses between the tires and the engine.

Duty Cycle Evaluation

An example of the duty cycle for Vehicle 10 on 14 October 2019 is shown in Figure 2.

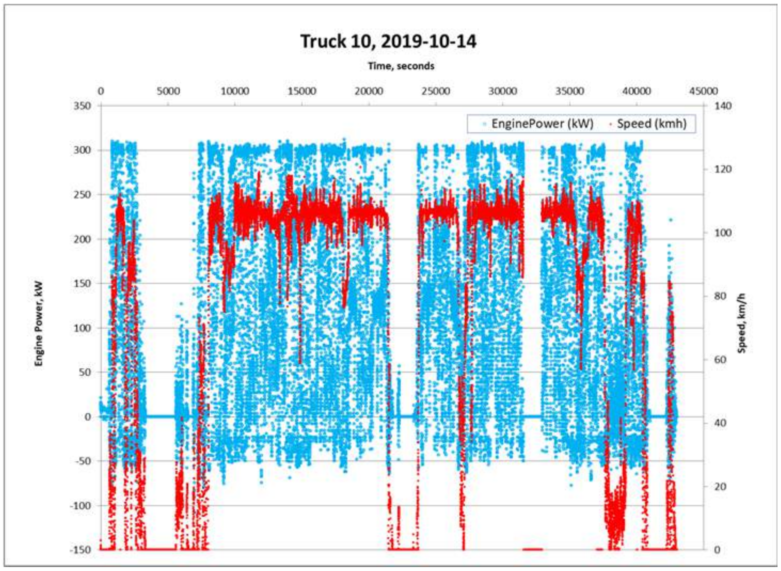


Figure 2: Example Duty Cycle, Truck 10

This data shows both the calculated engine power in kilowatts and the truck speed plotted against time. Duty cycle statistics such as average engine power and speed, peak power and speed, etc. are easily calculated. The entire duty cycle spans 11 hours and 55 minutes. Required engine power versus time is the key requirement and, as described later in this paper, dictates the dimensions of the fuel cell – battery hybrid drive system.

During this nearly 12-hour duty cycle, peak speeds of approximately 110km/hour (68mph) were recorded, and there were five 30-minute or longer periods with sustained speeds over 90km/hour (56mph), with the longest period at nearly one hour duration. A histogram of truck speed is shown in Figure 3.

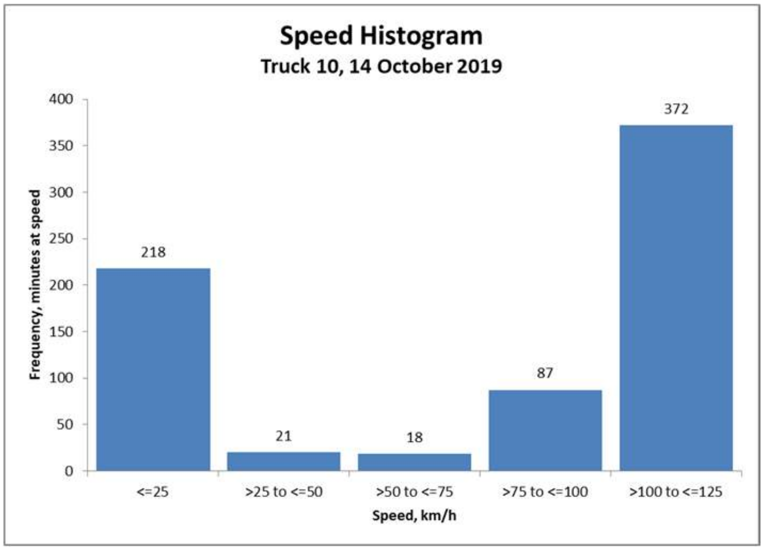


Figure 3: Histogram of truck speed for the duty cycle in Figure 2

Engine power requirements up to 312kW (418HP) were calculated in this duty cycle. These periods of peak power were required when the truck was accelerating and when the truck was traveling at high speeds.

There were also periods when calculated power was less than zero, indicating the truck was decelerating; the maximum negative calculated power for this duty cycle was -108kW. These are instances when a truck with an electric drivetrain and regenerative braking can capture energy, thereby increasing the truck efficiency. A histogram of engine power for Truck 10 is shown in Figure 4.

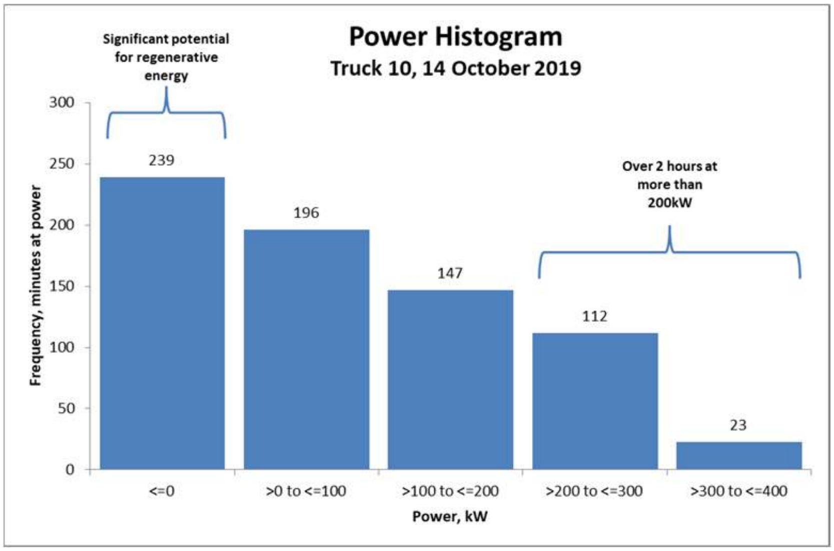


Figure 4: Histogram of truck power for the duty cycle in Figure 2

Additional statistics were calculated for each truck for each day of the RoLR event. A sample of these statistics for two days of Truck 10 operation is shown in Table 2.

Table 2: Truck 10 Statistics

	14 October 2019	25 October 2019
Mean Engine Power, kW	100	121
Peak Engine Power, kW	312	311
Mean 30 minute rolling average Power, kW	112	136
Peak 30 minute rolling average Power, kW	143	170
Total Distance traveled per day, km (mile)	836 (518)	801 (496)

Mean 30-minute rolling average power, including power less than zero, was calculated to provide an indication of required sustained power levels versus simply considering average power requirements. And the peak 30-minute rolling average power for each day was recorded. For the data shown in Table 2, there is a period during 14 October when the engine was required to deliver an average of 143kW for 30 minutes, and the average 30-minute rolling power requirement is 112kW. Reviewing the entire data set for Truck 10, it is noted that on 25 October the highest power requirement was required, with a peak 30-minute rolling average power requirement of 170kW. The reason for this higher power requirement is thought to be because two heavier loaded trailers were in tow rather than two lightly loaded trailers, hence a noticeably greater power requirement.

Daily mileage was fairly consistent for the 15 days where Truck 10 had valid data. The average mileage was 863km (535 mile) with a minimum of 801km (496 mile) and a maximum of 944km (585 mile). The highest single-day mileage for all trucks in the data sets was Truck 1 at 1,320km (819 mile) on 8 October 2019.

These same power and distance calculations were made for the other trucks in the data set.

Also of interest are the hours of operation of the trucks. Truck 10, with an average operation of 12.3 hours per day, was operated similarly to most of the other trucks in the event. The longest day of operation for Truck 10 was 15.8 hours on 18 October 2019. Truck 1 deviated from this pattern, as it had four days where it was operated more than 20 hours, with two of those days a full 24 hours. There were a few periods during each of these four days, typically 1 to 1.5 hours duration, when the truck was stationary but, otherwise, the truck was either moving or stopped for only short periods. Truck 5 also had days of 20 or more hours of operation but, on each of those days, there were approximately five hours (total) over one or two blocks during the operating period in which the truck was stationary (refer to Figure 5).

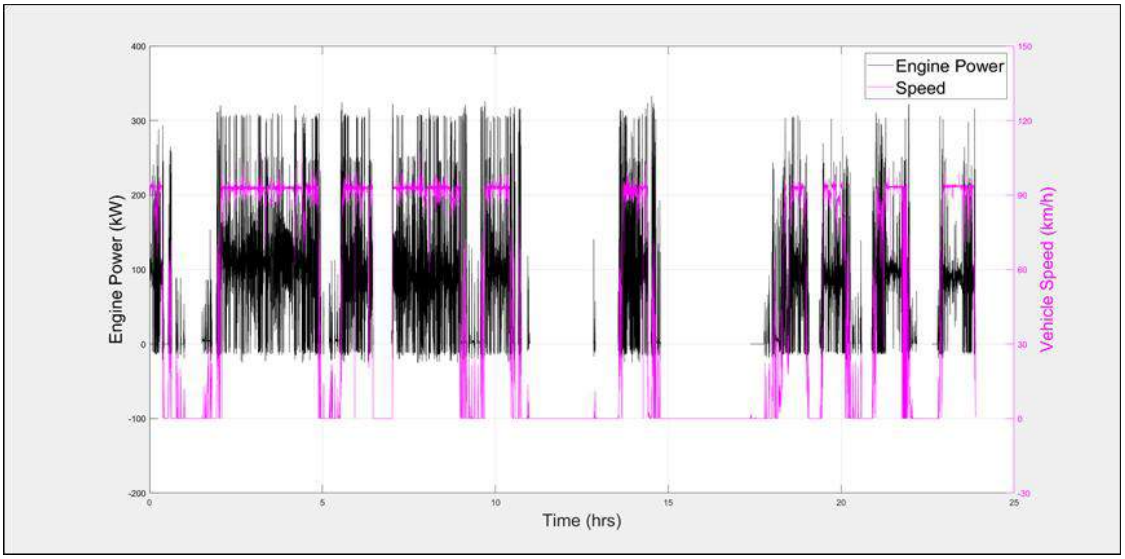


Figure 5: Truck 5 duty cycle with periods of inactivity, 11 October 2019

Fuel Cell – Battery Hybrid Truck Metrics for Comparison

The objective of this study is to design fuel cell – battery hybrid architectures which meet the NACFE RoLR duty cycles, followed by simulating performance of those hybrid architectures operating on those duty cycles and, finally, reporting performance metrics. The performance metrics are useful for estimating total cost of ownership of the hybrid truck when operated in duty cycles similar to the RoLR event. These performance metrics are presented in Table 3.

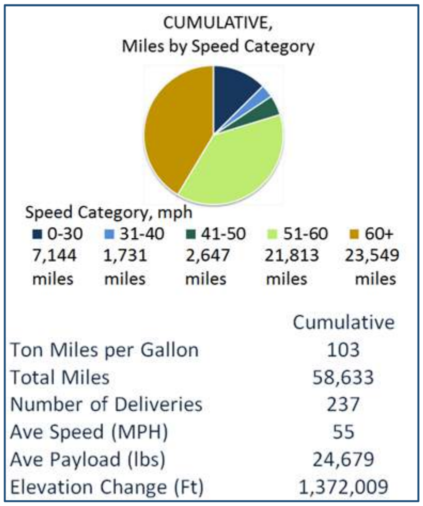
Table 3: Fuel cell hybrid vehicle performance metrics

Metric	Notes
Fuel cell power, kW	**Modeled fuel cell power***
Fuel cell current, amps	**Modeled fuel cell current***
Battery power, kW	**Modeled battery power***
Battery current, amps	**Modeled battery current***
Battery State of Charge (SOC), %	**Modeled battery SOC***
Battery peak C-Rate	**Highest modeled C-Rate over the duty cycle**
Hydrogen consumption per day, kg	**Modeled hydrogen requirement based on fuel cell operating parameters**
Hydrogen consumption, kg/100mile	**Hydrogen consumption, kg/100mile, is calculated**

***data points are generated at 1Hz frequency over the duty cycle**

Additional performance metrics can be derived or estimated from those shown in Table 3 and are important for informing the practicality and infrastructure requirements of fuel cell hybrid trucks in regional haul applications:

- Diesel miles per gallon (mpg) equivalent, based on the energy content (LHV) of diesel and hydrogen, is a useful efficiency comparison.
- Freight weight maximum possible is estimated by comparing the estimated weight of the fuel cell hybrid solution including fuel storage against the estimated weight of the diesel drive train. A higher weight fuel cell solution will reduce the available payload, and vice-versa.
- Range is estimated knowing the energy consumption per distance and the fuel storage system capacity on the truck. Fuel storage capacity is dimensioned from commercially-available hydrogen storage tanks and available space on the truck for tanks.
- Refill time and frequency is based on the capacity of the fuel storage system, location of fuel stations, and by reviewing state-of-the-art heavy-duty refueling system parameters.



	Cumulative
Ton Miles per Gallon	103
Total Miles	58,633
Number of Deliveries	237
Ave Speed (MPH)	55
Ave Payload (lbs)	24,679
Elevation Change (Ft)	1,372,009

Figure 6: NACFE RoLR summary data, including payload.

- Infrastructure requirements are estimated based on the duty cycle range requirements and the truck fuel storage system.
- Performance of the fuel cell system for expected temperature and elevation ranges.
- Freight ton efficiency, based on the estimated payload and the energy content of the hydrogen consumed by the fuel cell truck
- Estimated tare weight of the fuel cell truck.
- Freight weight varied from day to day and truck to truck. NACFE did not have actual measurements of weight, but inferred weights based on analysis of engine data. The Run on Less website summarized the 17 days of data from 7 October to 23 October as having an average payload weight of 24,679 (11,218kg), refer to Figure 6. Some trucks ran at maximum load, some returned empty trailers during their routes, so the whole spectrums of weights are represented.
- Chassis length versus fuel storage capacity; longer chassis could store more fuel and potentially impact the frequency of refueling and number of required fueling stations.
- Axle loading/distribution of tare weight can be estimated based on the hybrid drive system dimensions, weights, and placement on the truck chassis.

Examples of the hybrid designs selected for the NACFE RoLR trucks are reviewed in the following section.

Design of the Fuel Cell Truck to Meet Drive Cycle Requirements

Today, combustion engines for heavy-duty trucks servicing regional delivery applications are often rated from 150kW to 450kW peak power. Therefore, the hybrid truck "engine" should also be capable of delivering similar power for the same gross vehicle weight rating, chassis design, tires, and aerodynamic properties.

Refer to Figure 7 for a high level description of the fuel cell – battery architecture. In this architecture, both the fuel cell and the battery are connected to the high voltage DC traction bus. Power demands are met by a combined response from the fuel cell and battery; i.e., both the fuel cell and battery fulfil the power demand. The Ballard FCmove® fuel cell system responds to power demands at 40 amps/second, and the battery response is considered instant. Typical vehicle controllers will allow the battery to provide as much current to the DC bus within the limits of the battery C-rate and SOC, and the fuel cell will deliver power based on the SOC of the battery; essentially, the fuel cell maintains the battery SOC in addition to supplementing battery power to achieve total power requirements. Importantly, all energy for the drive cycle is provided by the hydrogen in the storage tanks on the truck – the truck is not "plugged-in" to the grid to charge the batteries.

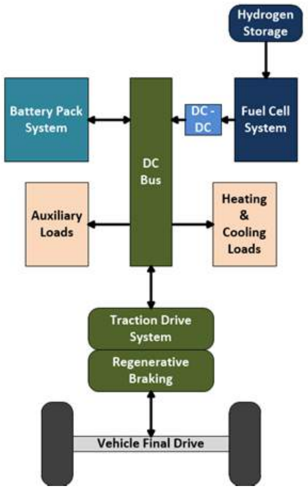


Figure 7: Fuel cell – battery hybrid drivetrain.

Vehicle designers have a choice in dimensioning the fuel cell power and battery energy capacity for their vehicles, and different designs are in evidence today for the early fuel cell truck demonstrations being played-out in California and other regions. Some designs consist of a fuel cell with relatively low power output, for example less than 100kW, coupled to a battery of relatively high energy capacity – this is the so-called "range-extender" architecture. In this design, the fuel cell extends the range of the battery while avoiding excessively large and heavy battery solutions.

The other solution is to employ a fuel cell with relatively large power output, for example 200kW or more, coupled to a battery of relatively low energy capacity – this is the so-called "fuel cell dominant" architecture. This design is intended to offer the power, range, payload, and utilization similar to current diesel trucks, and is viewed by experts[v] as the likely most prevalent future design as costs of fuel cells, hydrogen fuel, and infrastructure continue decreasing. The fuel cell architectures presented herein are based on an investigation of fuel cell dominant architectures.

Manufacturers of fuel cell solutions for heavy-duty applications are developing families of products to meet end-use requirements. These fuel cell product families will leverage the inherent flexibility of fuel cell technology, where individual cells are "stacked" in series to deliver desired voltage and current characteristics, and these stacks can then be electrically combined in parallel to deliver power needed for the application. This is similar to families of current combustion engines where variations on engine parameters such as cylinder bore and stroke and number of cylinders contribute to performance characteristics to meet application power and torque requirements. Refer to Figure 8 for an example of fuel cell stacks integrated into a heavy-duty fuel cell module.

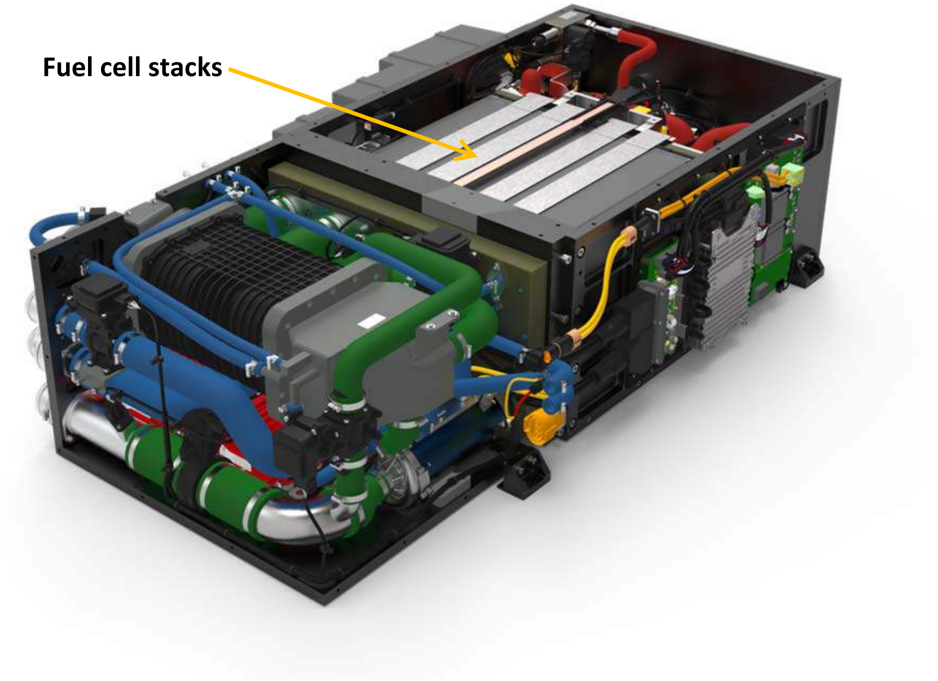


Figure 8: Ballard FCmove® fuel cell module. Power is increased by adding fuel cells to the module.

Given that the hybrid solution should deliver between 150kW-450kW power, the solution space selected for this study consisted of fuel cell power in increments of 100kW. Essentially, fuel cells of 100kW, 200kW, 300kW, 400kW, etc. are considered as possible solutions, and the capability of each of these fuel cells is evaluated against the duty cycle requirements from the NACFE RoLR event. Battery capacity for each fuel cell solution is determined based on the gap between the power delivered by the fuel cell and the power required by the duty cycle. Therefore, a fuel cell power and battery capacity architecture is selected which meets the duty cycle requirement for each day of operation for a given truck. And finally, a single hybrid architecture for each truck which satisfies all days of the RoLR event for that truck is selected.

Hydrogen fuel consumption over these duty cycles is modeled and the hydrogen storage tank requirements are estimated from supplier data sheets. The size and number of tanks and their placement on the trucks is key to achieving the range requirements while minimizing impacts on payload and fueling infrastructure needs. Studies have indicated that trucks theoretically have ample capacity to store enough hydrogen to achieve truck ranges sufficient to reach a large portion of applications, refer to Figure 9.[vi]

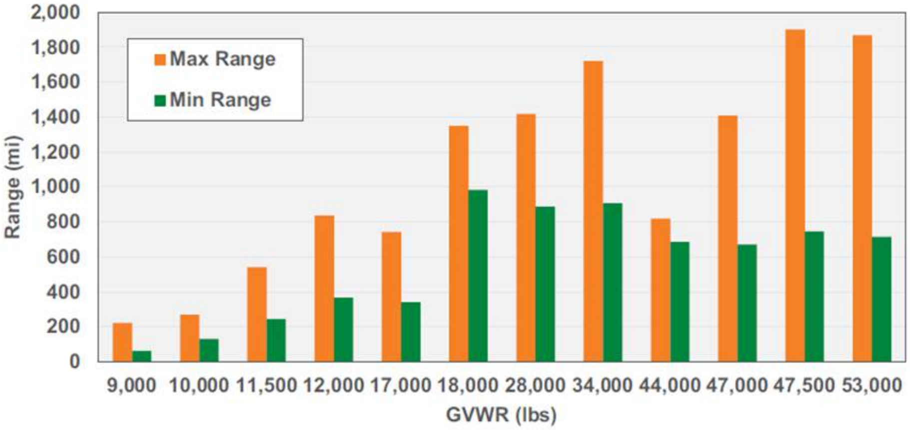


Figure 9: Maximum and Minimum medium- and heavy-duty truck range at 700 bar compressed hydrogen storage.

Although the industry has not yet settled on a standard pressure or configuration of tanks for heavy-duty trucks, suppliers are supporting early fuel cell truck demonstrations with tank solutions of various sizes and pressure ratings.

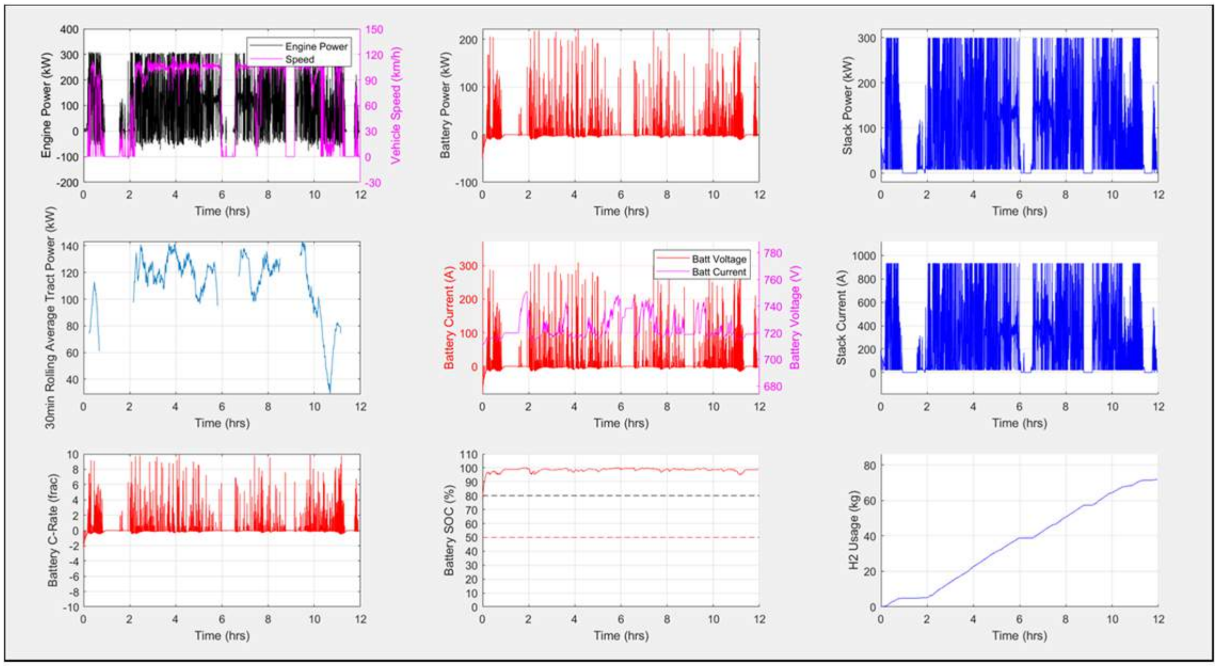
The selected architectures and modeled fuel consumption for each of the eight trucks is shown in Table 4. This data shows that seven of the eight trucks are satisfied with a 200kW fuel cell and moderately sized battery. An important parameter in the analysis of the battery capacity is the allowable C-rate for the battery. For this analysis, Ballard allowed a maximum rate of 10C, discharge and charge. For comparison, the recently demonstrated Kenworth Class 8 drayage trucks for the Toyota “Project Portal” utilize a 12kWh battery with approximately 230kW of fuel cell power – these batteries are estimated to operate at approximately 20C discharge rate to deliver the rated 500kW of power.[vii]

Fuel cells for heavy-duty applications are generally liquid cooled, and Ballard fuel cells are additionally humidified, and operate at higher pressures. These features enable long lifetime, start up capability (without external energy input) to -25°C (-13°F), and stable operation and delivery of rated power over a temperature range of -30°C to 50°C (-22°F to 122°F), humidity from 5-100%, and elevation to 1000m (3,300 ft). Above 1000m, fuel cell power output de-rates approximately 4% per 1000m elevation gain, where this de-rate is caused by lower oxygen partial pressure in the thinner air and increased parasitic energy requirement of the systems supplying air to the fuel cells.

Performance Comparison: Fuel cell electric truck vs. conventional internal combustion engine

Using the duty cycles and analysis process described in the preceding sections, a fuel cell – battery hybrid powertrain solution was developed, hydrogen requirements estimated, and performance metrics generated for each of the eight trucks in the study.

An example of the automatically generated data for Truck 10 on 14 October 2019 is presented in Figure 10.



FC System: 3 x 100kW

Max Battery C-Rate: 10

Mean 30 minute rolling average Engine Power: 111.7kW

Distance travelled per day: 836.1km

H2 consumption per 100km: 8.6kg/100km

Battery Pack: 22.4kWh

Mean Engine Power: 100.2kW

Peak Battery C-Rate: 9.9

Total H2 consumption per day: 71.9kg

Figure 10: Automatically generated output from simulation tool for Truck 10 on 14 October 2019.

Evaluating the duty cycle for each day, the hybrid architecture for Truck 10 was selected at 300kW fuel cell system coupled with at 23kWh battery pack. Using this combination for the powertrain, all duty cycles for Truck 10 are successfully completed while keeping battery C-rates at 10C or lower, and battery SOC above 78%. This process was completed for the other seven trucks in the study, with the results presented in Table 4.

Table 4: Hybrid architectures and hydrogen requirements by truck.

Truck	Fuel cell power, kW	Battery, kWh	Daily distance, mile	H2 daily consumption, kg	H2 consumption, kg/100mile	Battery C-Rate, max.	Battery SOC, min.
1	200	20	370 – 819	47 – 110	11.5 – 14.2	**7**	**20**
2	200	17	193 – 510	24 – 61	10.5 – 14.0	**9**	**56**
4	200	15	348 – 596	42 – 85	11.6 – 14.2	**10**	**65**
5	200	32	79 – 714	10 – 104	10.8 – 14.7	**5**	**18**
6	200	15	261 – 413	27 – 44	9.6 – 11.1	**9**	**64**
7	200	21	139 – 525	20 – 78	12.8 – 17.4	**7**	**20**
8	200	15	216 – 503	25 – 62	11.4 – 14.2	**9**	**64**
10	300	22	496 – 585	72 – 86	13.6 – 16.6	**10**	**78**

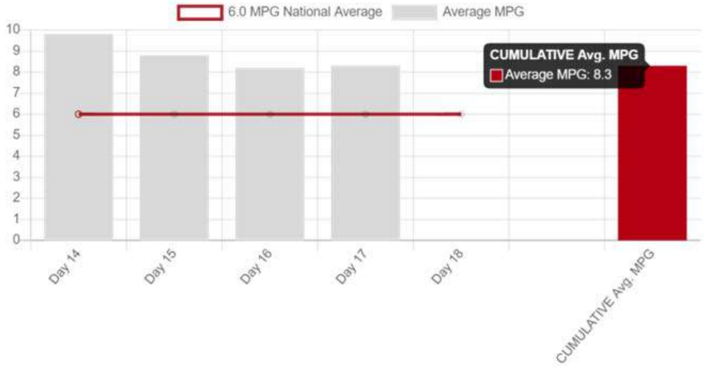


Figure 11: NACFE RoLR Cumulative Average Fuel Consumption Rate.

Simulated average fuel consumption rate for these eight trucks is 12.9kg/100mile (8kg/100km) and the cumulative hydrogen fuel consumption is 6143kg over 47,664 miles. The hydrogen fuel consumption can be converted to DGE (diesel gallon equivalent) using a ratio of fuel energy contents; average fuel consumption of the fuel cell trucks is 8.8 miles/DGE. This compares to 8.3 miles/gallon for the 10 diesel trucks operating over 58,633 miles in the RoLR event. Although not undertaken in this study, it is likely possible to improve (reduce) hydrogen fuel consumption by optimizing the hybrid architecture, for example by dimensioning the fuel cell so that it spends a majority of time operating at high efficiency. A typical fuel cell module efficiency curve is shown in Figure 12.

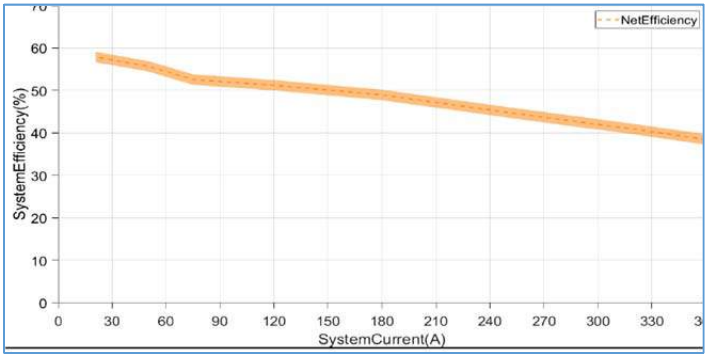


Figure 12: Typical heavy-duty fuel cell module efficiency curve.

For the freight industry, fuel cell electric powertrains offer four key advantages over a pure battery powertrain: longer range, greater power, more payload capability, and faster refueling leading to high utilization of the truck asset.

Environmental Gains

Most heavy-duty vehicles are powered by diesel engines that emit high levels of particulates, nitrogen oxides, and other pollutants. Based on their mileage and fuel consumption, freight vehicles are among the highest contributors to GHG emissions and street level pollution.

Governments have set aggressive GHG reduction targets, and due to the high volume of freight transport vehicles on the road, moving to zero-emissions in freight transport will go a long way to meeting these targets.

When considering the environmental impact of a vehicle, emissions over the lifecycle of the vehicle should be considered. This includes emissions from sourcing and processing of raw materials to produce the vehicle, manufacturing and delivering the vehicle, production and use of fuel to power the vehicle, servicing and repairing the vehicle including emissions from production of replacement parts, and from refurbishment, recycling and disposal of the vehicle. Additionally, emissions from systems required to support the vehicle should be considered, such as emissions from land and property development for depots, construction or remodeling of maintenance facilities, and emissions from manufacture and delivery of fueling and charging equipment.

When considering fuel, a well-to-wheel analysis is typically used. This can be divided into two stages, typically known as well-to-tank, and tank-to-wheel. The former usually refers to fuel production from feedstock to its delivery to the vehicle's energy carrier, while the latter refers to energy consumption during vehicle operation (Figure 13).

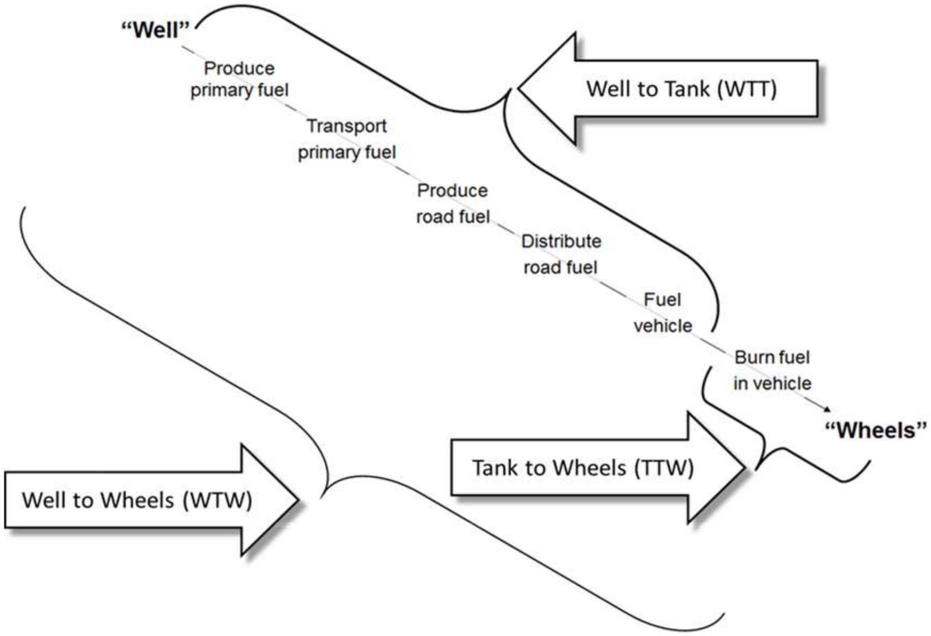


Figure 13: Well-to Wheels Analysis[viii]

When considering different vehicle types, this analysis more specifically refers to:

- In the case of fuel cell electric vehicles: hydrogen production, delivery and storage to the vehicle hydrogen tank, as well as consumption of hydrogen by the fuel cell truck during operation
- In the case of battery electric vehicles: electricity generation, transmission in the grid, charging the battery, and use during vehicle operation

Although hydrogen fuel cell vehicles only produce water during operation, the process of how hydrogen is produced, stored, delivered and refueled can produce greenhouse gas and cause environmental impacts.

The production of hydrogen plays a dominant role in the emissions of the fuel cell electric vehicle lifecycle. Hydrogen can be produced using a range of energy sources and technologies; however, today it is most common to produce hydrogen from fossil fuels, so called "brown" hydrogen. If carbon from the production process is captured and sequestered, then the hydrogen is referred to as "blue" hydrogen.

Electrolysis is a more sustainable way to produce hydrogen fuel. Renewable energies (such as solar and wind) are affected by seasonality and peak usage cycles resulting in overcapacity of electricity production which is often wasted. The marginal cost of renewable energies is near zero, and this low-cost energy can be used to produce "green" hydrogen by electrolysis of water with zero-emissions. Experts predict the cost of green hydrogen will compete with diesel fuel by 2030,[ix] with the important benefit of being a zero-emission fuel. Likewise, increased penetration of renewables on the electric grid improves the emissions profile of battery powered vehicles. The reduction in emissions can be quite dramatic in real-world applications. For example, by comparing diesel trucks with fuel cell trucks powered by hydrogen from centralized SMR, the latter can reduce 5%-26% fossil fuel consumption, and 20% to 45% of GHG emissions.[x] Transitioning from centralized SMR to solar electrolysis for hydrogen fuel production reduces GHG emissions by 86% on a well to wheel basis.[xi] The remaining 14% of GHG emissions are attributable to the grid electricity used for hydrogen compression at refueling stations.

A high percentage of the overall lifetime emissions of battery electric and fuel cell vehicles is actually a result of their end-of-life processes.

The process for recycling hydrogen fuel cells is well-established. At the end of a fuel cell's life span, the stack is recycled and refurbished. Carbon bipolar plates are reused several times, thereby minimizing waste. During the fuel cell stack refurbishing process, a new membrane electrode assembly (MEA) is integrated with the re-used bipolar plates and hardware. The old MEA is sent to a specialized facility that reclaims 95% of the platinum catalyst.

Refurbished fuel cells achieve the same specifications as a brand new stack, but are built using reused and recycled materials, minimizing landfill waste.

Hydrogen Fueling Infrastructure

Many heavy-duty trucks operate in fleets, and on well-defined routes. Two good examples of this are city delivery trucks returning to a central depot at night and drayage trucks operating at a port. Hydrogen fueling stations can therefore be installed at these centralized locations (depots and ports), for convenience. Additionally, the hydrogen fueling stations can be shared with other hydrogen applications besides trucks, like personal vehicles and light delivery trucks.

There are two methods of hydrogen production:

- Onsite production: hydrogen is produced by either electrolysis or steam methane reforming. Electrolysis involves the separation of the hydrogen from the oxygen using electrolyzers while steam reforming uses methane and water vapor to produce hydrogen.
- Offsite production: hydrogen is often a byproduct of industrial processes, and can be captured and stored for later use. And hydrogen from steam reforming or electrolysis can be produced offsite as well as onsite. The hydrogen can then be delivered by truck to the refueling station.

It is important to understand that the size of the hydrogen refueling infrastructure directly relates to the truck fleet size. A key consideration in this respect is ensuring that there is enough hydrogen available for the current fleet, while still taking future growth into account. Station requirements will be a function of the hydrogen carrying capacity on the trucks, the required range of the trucks, and the consumption rate.

The current limited distribution of hydrogen refueling stations and high cost of hydrogen create a challenge to deploy initial fleets of fuel cell-powered commercial vehicles. But public supports for construction of stations and production of low-carbon hydrogen are available to aid in the deployment and scale-up of hydrogen solutions. These include the California Low Carbon Fuel Standard[xii] and tax exemptions and financial incentives for renewable hydrogen production in Washington State.[xiii,xiv] For widespread commercialization, the price of hydrogen (dispensed from the pump) should be reduced to about $4 per kilogram, and many experts predict that this will be possible, at least in some regions, by as early as 2030.[xv] However, for applications where zero emission operation is required, a higher cost of hydrogen will be competitive – these early applications will help to scale the industry and drive down costs for wider commercialization. The initial focus on deployment of fuel cell electric regional logistics trucks operating on relatively fixed routes with central depots helps to address the hydrogen infrastructure challenge. Deployment of larger size fleets with longer distance routes should be considered, as this will drive down the cost of hydrogen by increasing the hydrogen demand and amortizing station costs over more vehicles and higher hydrogen throughput.

For the NACFE RoLR trucks, all are operating from a home base and returning to that base daily. Truck 1 has the highest daily hydrogen requirement of 110kg (refer to Table 4), and it is expected to be possible to fit storage tanks on the truck to accommodate this quantity of hydrogen fuel (Figure 9). This means that trucks only need to be fueled with hydrogen at the home base (or a single location anywhere along their routes), thereby simplifying the hydrogen infrastructure requirements by reducing the need for widely dispersed fuel stations. With a refueling rate of 5kg/minute, these fuel cell trucks can be refueled in less than 25 minutes, thereby enabling zero emission slip-seat or other high utilization freight movement requirements, including fully autonomous operations.

Cost Estimate

Ballard modeled the cost of owning and operating fuel cell hybrid heavy-duty trucks over the Truck 10 duty cycle from the NACFE RoLR event. Truck 10 was selected because, although it is operating at similar range as other trucks in the study, it is considered a worst case within the RoLR event because it has the highest power requirements and some of the highest hydrogen storage requirements, which results in higher cost and weight. Truck weight is important in applications requiring full-weight payloads, and it has been suggested[xvi] that lost capability to carry payload – a "payload penalty" – should be accounted for when analyzing truck costs.

Energy storage requirements – hydrogen storage tank and battery capacity – were estimated using the highest mileage traveled by Truck 10 and the maximum energy consumption rate for all days represented in the Truck 10 data set. In other words, a range of 944km (585 miles) and consumption rate of 10.3kg/100km yielded a fuel storage requirement of 108kg for Truck 10. Using an estimated specific density of 36kg tank weight per 1kg of hydrogen yielded a tank weight of 3910kg (8,600 lbs). Similarly, the weights of other components in the hybrid architecture were estimated, while accounting for components no longer needed in a fuel cell truck (such as the diesel engine, etc.) to yield a fuel cell hybrid truck estimated to weigh 3,520kg (7,750 lbs) more than a diesel truck. It is expected that the weight of the fuel cell truck will be reduced as the technology continues to mature, for example the specific density of hydrogen storage used in this example is approximately double the density targeted by US Department of Energy.[xvii] A similar process was used to calculate the weight of the battery truck, which is estimated to weigh 11,025kg (24,256 lbs) more than a diesel truck. Although some jurisdictions are allowing higher GVWR for zero emission battery and fuel cell trucks, those allowances were not included when considering payload penalty in this total cost of ownership (TCO) analysis.

In addition to payload penalty, other important parameters to consider in the cost study include infrastructure costs, cost of fuel and electricity, carbon tax, truck maintenance, fuel cell system efficiency, and cost of batteries, hydrogen storage and fuel cell system. For this analysis, Ballard varied these parameters to identify combinations where the fuel cell hybrid truck could be cost competitive with both a conventional diesel truck and battery-only truck. While the worst-case combination of duty cycles for Truck 10 were used to dimension the hydrogen storage system (per above), the duty cycle for 14 October 2019 was used for estimating the costs of fuel, maintenance, etc.

A modified version of the TCO Calculator available from NACFE was used for this analysis.[xviii] Combinations of parameters required for cost parity of the fuel cell hybrid truck with a battery-only truck and a conventional diesel truck are shown in Table 5.

Table 5: Conditions for fuel cell truck cost parity

For cost parity with a Battery Electric Truck (with payload penalty of $0.30/ton-mile):	
	Hydrogen cost of $6.75/kg and fuel cell system cost of $1,000/kW.
For cost parity with a Battery Electric Truck (with no payload penalty):	
	Hydrogen cost of $4.75/kg, fuel cell system cost of $350/kW.
For cost parity with a Diesel Electric Truck (with no payload penalty):	
	Diesel fuel cost of $3.85/gallon, hydrogen cost of $4/kg, fuel cell system cost of $100/kW.
or	Diesel fuel cost of $2.75/gallon, carbon tax of $100/ton, hydrogen cost of $4/kg, fuel cell system cost of $100/kW.

This simplified cost analysis shows that a hybrid fuel cell truck operating on the regional delivery route defined by Truck 10 can already today be cost competitive with a battery truck if payload weight is important, and that within a few years[xix] as the industry continues to scale-up the fuel cell truck is lower cost even if payload weight is not valued.

For cost parity with a diesel truck, a higher level of commercial maturity for hydrogen and fuel cell trucks will be required, especially with the current low cost of diesel. But with policy changes, eventual rising costs of diesel fuel, fuel cell and hydrogen technology advancements, and decreasing costs of hydrogen and fuel cell technology, the fuel cell truck can achieve cost parity with the diesel truck for this duty cycle.

Conclusion & Recommendations

Regional haul encompasses a wide range of potential duty cycles. The RoLR demonstration focused on 10 specific fleets representative of a significant number of operating vehicles in the segment. The RoLR fleet data highlights 10 example fleet operations where it is challenging for battery-only tractors to meet the requirements, especially if the capability to haul heavy payloads is important. Deploying fuel cell-battery electric hybrid vehicles is a way to avoid operational changes that may need to be considered when replacing diesel tractors with zero-emission vehicles on these RoLR example duty cycles.

Using the RoLR data, second-by-second engine power requirements were estimated and fuel cell hybrid architectures constructed to satisfy those power requirements. The majority of duty cycles could be met with a 200kW fuel cell and battery packs of 32kWh or lower capacity. Truck 10 required a 300kW fuel cell with a 22kW hour battery pack. Simulations of these fuel cell trucks operating over the duty cycles were completed, fuel cell and battery operational parameters reported, and fuel consumption estimated. Results indicate the fuel cell trucks can complete these duty cycles with a small reduction in payload carrying capacity and refueling times estimated at less than 25 minutes, thereby enabling high utilization zero emission freight movement.

For the freight industry, fuel cell electric powertrains offer four key advantages over a pure battery powertrain: longer range, greater power, more payload capability, and faster refueling leading to high utilization of the truck asset. Additionally, the full cost of implementing battery charging and hydrogen fueling infrastructure should be considered by the industry, as there could be further advantages, especially as owners scale-up their zero-emission fleets.

Development of cell technology and stack designs has advanced over the past 30 years, demonstrating durability, reliability, cost, power density, and recyclability improvements needed for heavy-duty applications. The fuel cell stack developments have been supported by leading governments and organizations and, equally important, these leaders have also supported the development and demonstration of the vehicles and fueling infrastructure. In several countries, regulations for truck emissions are tightening up and low-emission zones or corridors are been implemented. Europe has introduced truck emission reduction targets in 2019 and California is working on Advanced Clean Trucks standard. Those new regulations are going to drive the demand for zero-emission trucks.

Although fuel cell electric vehicles are currently more expensive to operate compared to battery electric and internal combustion engine commercial vehicles, they are set to become much lower cost as manufacturing technology matures, economies of scale improve, hydrogen fuel costs decline, and infrastructure develops. In less than 10 years, it will become lower cost to run a fuel cell electric vehicle than a battery electric or an internal combustion engine vehicle for certain commercial applications. This is the conclusion of a recent report titled “Fueling the Future of Mobility: Hydrogen and Fuel Cell Solutions for Transportation” jointly published by Deloitte China and Ballard.

Toyota, UPS, Nikola, Hyundai and Kenworth have all made headlines recently for high-profile hydrogen fuel cell projects. Meanwhile, several other major truck manufacturers have reported they are exploring zero-emission technology strategies to respond to increasing customer and regulatory pressures. Weichai, Bosch, Cummins, Daimler, Volvo and CNH Industries are examples of companies investing hundreds of millions of dollars towards the commercialization of fuel cell commercial vehicles.

These transactions, each initiated by a “heavy hitter” in the global transportation value chain, are the clearest indication yet of the positive future for fuel cells, underpinned by the trend toward electrification of mobility in a variety of large-market applications, including commercial vehicles.

Appendix

Data Logger Channels Used in this Study		
Channel	**Description**	**Use of the data**
EEC1_Engine_1__EngSpeed	Log rate = 10Hz	Sampled and interpolated at 1Hz and is used in the formula to determine engine power at the shaft
EEC1_Engine_1__ActualEngPercentTorque	Log rate = 10Hz	Sampled and interpolated at 1Hz and is used in the formula to determine engine power at the shaft
EEC3__NominalFrictionPercentTorque	Log rate = 10Hz	Sampled and interpolated at 1Hz and is used in the formula to determine engine power at the shaft
EC1__EngReferenceTorque	Static value per truck	Static value used to convert EEC1_Engine_1__ActualEngPercentTorque and EC1__EngReferenceTorque from percentage to N.m
Msg3__Speed	Log rate = 1Hz	Sampled and interpolated at 1Hz and is used to determine the distance traveled

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