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BALLARD

INFORMATIONAL

Zero emission drayage trucks

Technology and proven capabilities

Contents

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1. EXECUTIVE SUMMARY

Drayage operations are defined as "truck pick up from or delivery to a seaport, border point, inland port, or intermodal terminal with both the trip origin and destination in the same urban area". Drayage trucks will sit idle for long periods, stop/start with greater frequency creating less than optimal power performance, and the highest concentration of emissions within the transport service industry.

Hydrogen fuel cell powered trucks are currently the most advanced zero emission motive solution available to the drayage truck fleet owner.

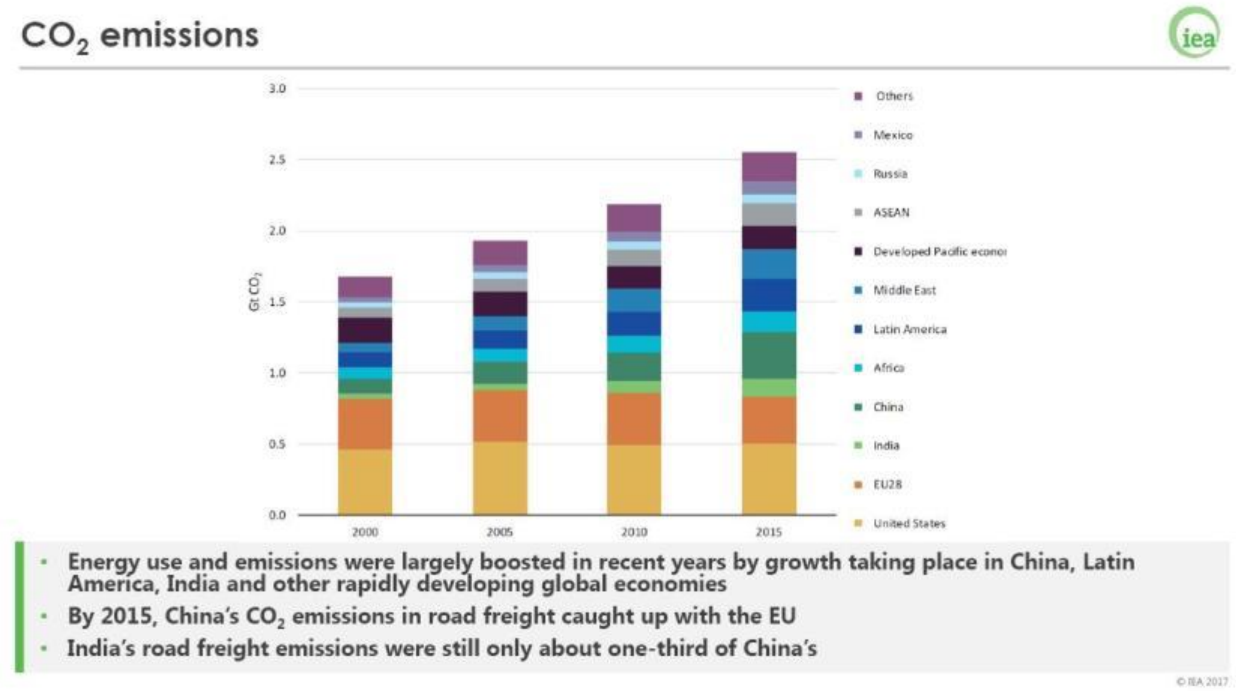
At Ballard Power Systems, significant and proven performance optics are now in view, and available for review by the end user and government organizations supporting the use of this technology in concert with hydrogen producers, particularly in California and other progressive regions.

This paper goes deeper into the drayage truck market and why the fuel cell-battery hybrid architecture makes the most sense for zero-emission freight applications.

2. EMISSIONS FROM HEAVY DUTY TRUCKS

Governments have identified that vehicle emissions are both a public health and environmental concern. Globally, it is recognized that diesel engine exhaust emissions are carcinogenic, air pollution is a major public health problem, and that road freight is the cause of approximately 17% of global NOx emissions and nearly half of total transport-related PM2.5 emissions[i].

In addition to health-related emissions, road freight is also a significant contributor to global CO2 emissions. Within the road freight sector, heavy duty (HD) freight trucks contribute disproportionately to emissions compared to other transport. In Europe, HD trucks represent only 4% of the on-road fleet but contribute 30% of the on-road CO2 emissions[ii]. The trend of rising emissions from road freight vehicles in the US bucks the trend of overall reduced CO2 emissions from fossil fuel combustion[iii].



- Energy use and emissions were largely boosted in recent years by growth taking place in China, Latin America, India and other rapidly developing global economies
- By 2015, China's CO_2 emissions in road freight caught up with the EU
- India's road freight emissions were still only about one-third of China's

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Figure 1 Vehicle Emissions

Global registrations of heavy-duty trucks, including both new vehicle sales and second-hand imports, have grown from 2.7 million units sold in 2000 to nearly 4.4 million in 2015[iv]. With growing international trade and globalization of manufacturing supply chains, CO2 emissions from road freight are expected to increase four-fold by 2050 to more than 8,000 metric tonnes of CO2 annually[v].

3. WHY ZERO EMISSION DRAYAGE TRUCKS ARE IMPORTANT

Drayage trucks – heavy duty trucks operating in and out of the ports – are commonly used for transporting shipping containers (Intermodal Containers) to and from the ports. These trucks are typically Class 8 heavy duty diesel powered trucks. As noted above, the emissions from these trucks have a negative impact on both human health and the environment. As ports are often located near population centers, the communities near the ports suffer disproportionately from emissions associated with the drayage trucks serving the ports. Governments have recognized the importance of reducing emssions from these trucks and are taking action to introduce requirements for low and zero emission technologies.

California has identified that diesel emissions at freight hubs are a significant source of air toxins and is targeting reduced emissions from HD trucks to reduce or eliminate health and quality of life impacts on the communities affected by these emissions at these ports and hubs[vi]. The largest ports in California are the San Pedro Bay Ports, consisting of the Ports of Los Angeles and Long Beach, where these two metropolitan ports alone have more than 17,000 HD drayage trucks registered to operate. The California Sustainable Freight Action Plan released in 2016 calls for preferential port access to zero-emission trucks and, beginning in 2035, all trucks registered in the California Ports Drayage Truck Registry must be zero emissions.

California is not alone in working for lower HD truck emissions. The Ports of Seattle and Tacoma, for example, are also addressing emissions from trucks, and other pollution sources at the ports. And globally, governments have already established many low emission zones and are progressively working to establish zero emission zones (ZEZs), as shown in Table 1, by restricting access or levying taxes[vii]. Only zero-emission vehicles – effectively only battery or fuel cell vehicles – will be permitted in these ZEZs.

Table 1 Selected Low and Zero Emission Zones - Cities

Austrian LEZs: lorries over 3.5T	Italy/France, Mont Blanc tunnel: lorries only
Belgium, Antwerp, Gent: all vehicles with four & more wheels	Netherlands: lorries over 3.5T GVW
Czech Republic, Prague: lorries over 3.5T or 6T	Portugal, Lisbon: Petrol & diesel, light duty and heavy duty
Denmark: All diesel-powered vehicles above 3.5T	Sweden: All heavy, diesel-powered trucks and buses
Finland: Buses and garbage trucks (dustbin lorries)	UK, London: Vans and similar over 1.205T unladen
Germany: All vehicles with four wheels	UK, London: vehicles over 3.5T GVW
Greece, Athens: All vehicles, vehicles over or under 2.2T	UK: Norwich, Oxford, Brighton: Public service buses only
Italy: All vehicles, including mopeds and motorcycles	Additional LEZs are expected in Norway, Paris

4. DRAYAGE TRUCK MARKET

Shipment of commercial goods in intermodal containers proceeds at a massive scale around the world. Container shipments can reach nearly anywhere on a regular schedule and, compared to other modes of transport, container shipment is efficient and affordable.

The quantity of containers handled is measured in TEU – Twenty foot Equivalent Units – and in 2016 exceeded 700 million TEUs globally and is projected to continue growing. The Port of Shanghai is the busiest container port in the world, handling approximately 37 million TEUs in 2016 [viii]. Amsterdam, the busiest container port in Europe, handled more than 13 million TEU in the same year. And, in California, there are over 17,000 HD trucks registered in the San Pedro Ports' Drayage Truck Registry[ix] serving the Ports of Los Angeles and Long Beach handling a combined total of more than 16 million TEU in 2017.

Clearly, HD drayage trucks globally number in the hundreds of thousands, and reducing or eliminating harmful emissions from these trucks is becoming a priority as evidenced by the efforts of California, China, Japan and the EU.

5. SPECIFIC REQUIREMENTS FOR DRAYAGE TRUCKS

At the California ports and other commercial environments where independent truck operators are working, drayage trucks must be “full service” – it is not permissible for freight dispatchers to dictate or manage which trucks operate on which routes; therefore, any given truck must be capable of any route and load.

At the San Pedro Bay Ports, key performance expectations for the trucks are summarized in Table 2[x]:

Table 2 San Pedro Bay Ports - Key Performance Expectations for Trucks

Performance Parameter	Value
Daily Range	Up to 320 km (200 mile)
Number of turns per day	3 typical, 4 to 5 on a good day
Refueling interval	2-4 days for diesel, daily for natural gas
Gradeability and Startability	6% on near-port bridges; ability to accelerate from 0 to 65 km/h (40 mph) on grade
Freight Load	Containers up to 20,000 kg (44,000 lbs)
Durability: Vehicle lifetime – miles	800,000 km (500,000 miles) or more
Durability: Vehicle lifetime – years	target 10 years (8 minimum)
Speed	From creep to 105 km/h (65 mph)
Uptime / availability	Minimum 90%

These performance parameters indicate that users expect high performance and utilization from their trucks – downtime for recharging, refueling, excessive maintenance, or equipment failures will not lead to commercial success.

Required truck operational parameters will depend on the port and region of operation for the truck. Recent data[xi] for truck fleets operating from the Port of Oakland indicates much higher trip lengths, compared to trucks operating from the San Pedro Bay Ports, with 40% of trip distances exceeding 160 km (100 miles) and 17% exceeding 320 km (200 miles).

Drive cycles characterizing the speed of the truck versus time are available for various heavy duty drayage routes. For example, the California Air Resources Board (CARB) HHDDT (heavy heavy-duty diesel truck) Composite drive cycle is shown in Figure 2. This drive cycle includes creep, transient and high speed cruise portions. There are approximately 250 seconds of creep, typical of slow operation or waiting in a queue at a port; 700 seconds of transient operation, typical of near-port driving; and 2000 seconds of highway driving. Drive cycles help to visualize truck operation and are used in modeling and testing vehicle performance.

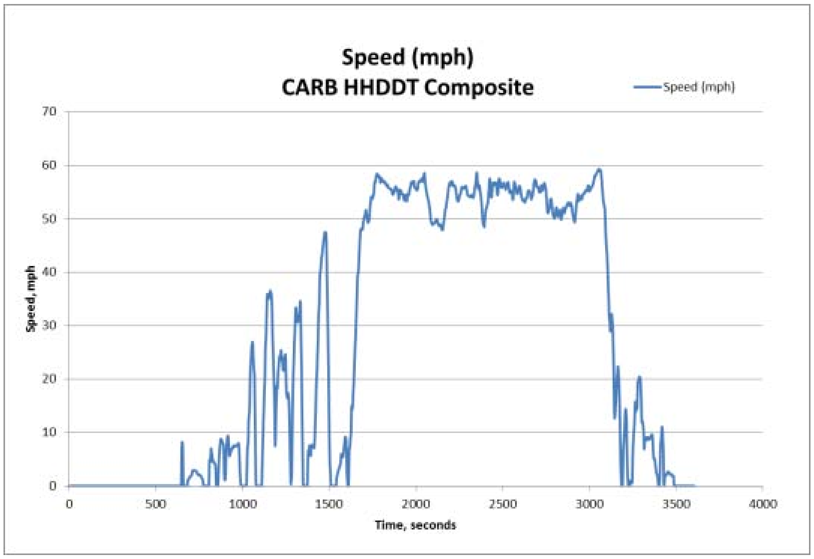

Figure 2 CARB HHDDT Composite Drive Cycle

Using traction power equations detailed later in this paper, the instantaneous power requirements and the energy required for the entire drive cycle can be estimated. For example, a loaded Class 8 HD truck traveling at 90 km/h (55 mph) on the highway driving portion of the CARB HHDDT Composite cycle will require approximately 120 kW of power and 67 kW·h of energy over the 2000 second (33 minute) duration. Operating this same truck at the same speed for 3600 seconds (1 hour) will require approximately 120 kW·h of energy. Auxiliary loads, if present, should be added to the drive cycle requirements to achieve the total required power and energy.

Understanding the duty cycle (drive cycle plus auxiliary loads) of the truck is critical when selecting the proper zero emission technology and architecture for the truck. A suitable architecture for a truck operating at low speeds with small auxiliary loads is significantly different than the architecture for a heavy duty truck operating for extended periods at highway speed with large auxiliary loads and acceleration requirements. However, since all trucks operating in a commercial drayage operation must be “full service”, the truck architecture must be suitable for the worst-case duty cycle.

A hybrid drivetrain architecture consisting of a fuel cell and a battery is particularly well-suited for heavy duty applications that include extended high power operation and require long range without sacrificing truck payload. Additionally, this fuel cell / battery architecture is durable, reliable, and meets the requirements of zero emission and lifetime.

6. THE FUEL CELL SOLUTION

The combination of the drive cycles and required vehicle performance, range, and lifetime establish high-level requirements that can be used to evaluate the suitability of specific drivetrain configuration. Ballard Power Systems used the above drayage truck requirements as inputs to simulate the performance of a fuel cell – battery hybrid architecture operating in a drayage truck application. The results from our investigation of the CARB HHDDT Composite Cycle simulation are presented in this section.

The CARB HHDDT Composite Cycle is a four mode cycle developed by the California Air Resources Board (CARB) with West Virginia University and is intended to represent heavy-duty commercial truck operation. The cycle consists of four segments: an initial idle segment of about 10 minutes, and creep segment of about 4 minutes, a transient segment of about 11 minutes, and a highway cruise segment of about 35 minutes. Additionally, the Ballard team added an uphill acceleration profile to the front-end of every second composite cycle to investigate the effects of accelerating from 0-50 km/h (0-30 mph) in 16 seconds (acceleration = 0.9 m/s^2). This was intended to simulate for example sustained acceleration up a 6% grade, as shown in Figure 3.

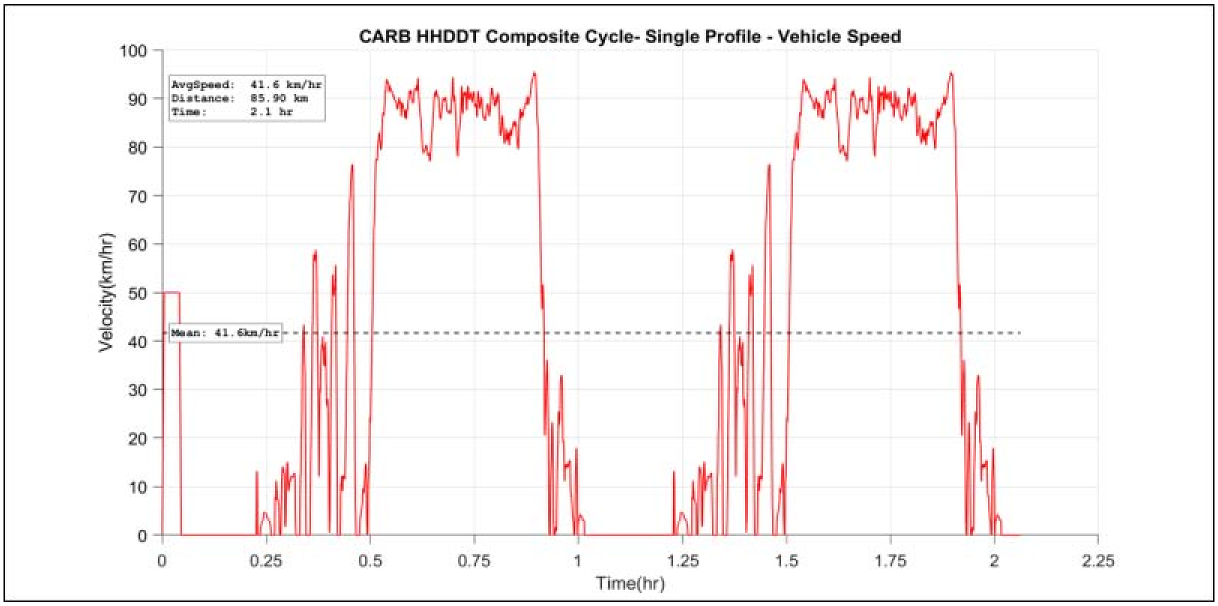

Figure 3 Velocity Profile, Uphill Acceleration & CARB HHDDT Composite

The combined steep grade plus HHDDT Composite cycle was repeated 16 consecutive times with no rest period between cycles (the HHDDT Composite already includes 10 minutes of idle), resulting in 685 km (425 miles) of operation over a 16 hour period, as shown in Figure 4.

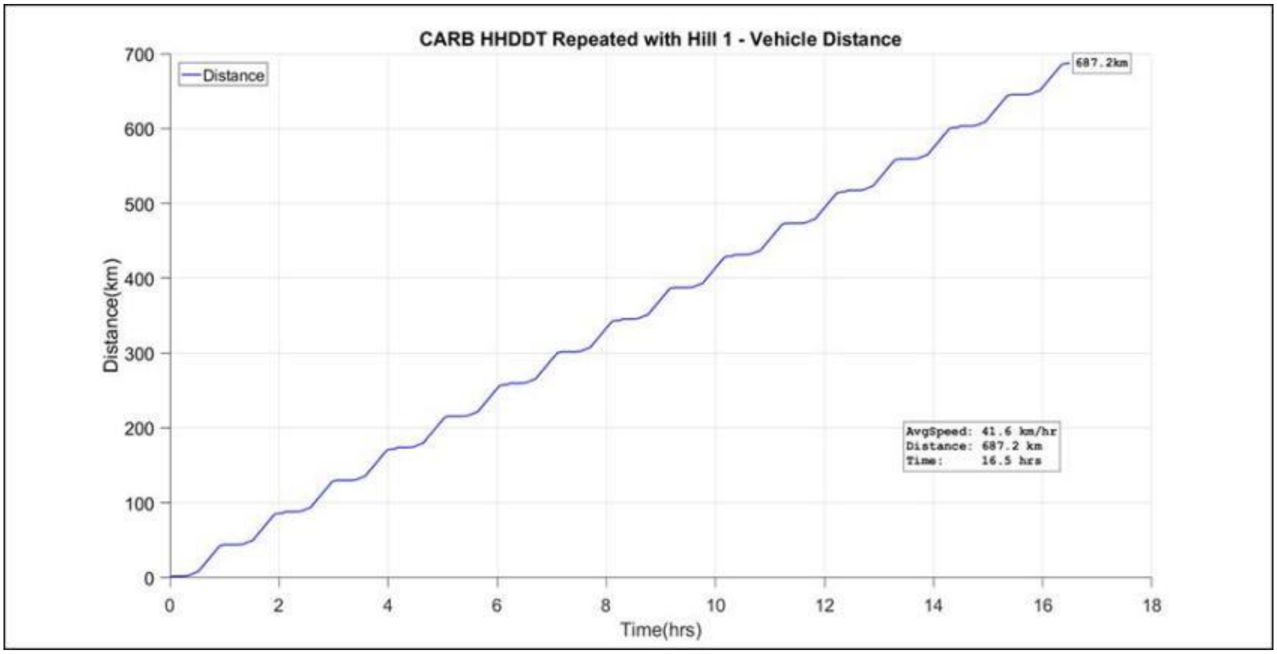

Figure 4 Distance Versus Time

The truck parameters chosen for this investigation are characteristic of a HD truck and are shown in Table 3:

Table 3 Truck Parameters

Truck Parameter	Value
Mass	32,545 kg (71,600 lbs)
Coefficient of Rolling Resistance	0.006
Coefficient of Drag	0.6
Frontal Area	2.8 m x 3.7 m (9.2 x 12.1 ft)
Traction Drive Efficiency	90%

These parameters are used in the traction power equation, shown in Figure 5, along with the velocity profile, to generate the required mechanical power. Note that changes in elevation, if known, can be accounted for in the equation. The required electrical power is calculated assuming a 10% loss through the traction drives.

$$Power_{mech} = v\left(\overbrace{ma}^{\text{Kinetic}} + \overbrace{mgC_{roll}}^{\text{Rolling}} + \overbrace{0.5\rho_{air}C_{drag}A_{front}v^2}^{\text{Drag}} + \overbrace{mgsin(\theta)}^{\text{Gravitational}}\right)$$

Figure 5 Traction Power Equation

The calculated traction power for a single, two-hour profile are shown in Figure 6. The two-hour profile is repeated 8 times to create the 16 hour profile. During the initial uphill acceleration, nearly 800 kW needs to be supplied to the traction drives. (The 800 kW may exceed the capability of the traction drives, and the truck may not meet the acceleration as modeled.) The traction battery in combination with the fuel cell provides this peak power. The ability to share the load is a significant beneficial characteristic of a fuel cell / battery hybrid architecture.

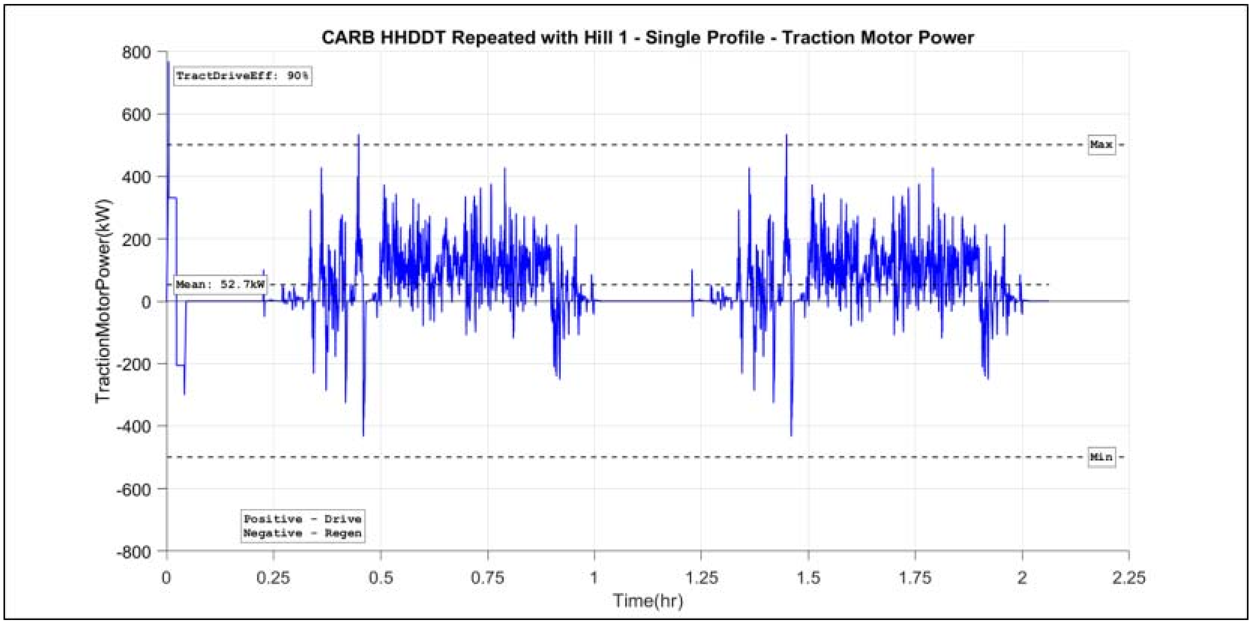

Figure 6 Traction Motor Power

A high-power/low-capacity battery supports the high-power transient peaks in the profile and captures the regen power during deceleration. A low-power and relatively light-weight fuel cell system and hydrogen tanks provide steady-state power to maintain the battery SOC (state-of-charge). In this configuration, the battery provides the power (kW), and the fuel cell provides the energy (kW·hr). Alternatively, in a battery-only system, the battery is sized to meet the energy requirement, resulting in a very heavy battery system that reduces the vehicle payload.

The profile ~53 kW mean traction power is shown in Figure 7. A drive cycle with lower speeds or a lighter weight truck will require lower average traction power.

Vehicle speed is an important contributor to total required traction power. As shown in Figure 6, the drag power is a function of velocity-cubed, and is a significant component of mechanical power at high speed. This is shown graphically in Figure 8 where the mechanical power required to overcome drag becomes more significant above ~70 km/h (45 mph). The required traction power at 100 km/h (62 mph) is more than double the power at 70 km/h (45 mph). (Figure 8 assumed the truck is operating at constant speed on flat ground.)

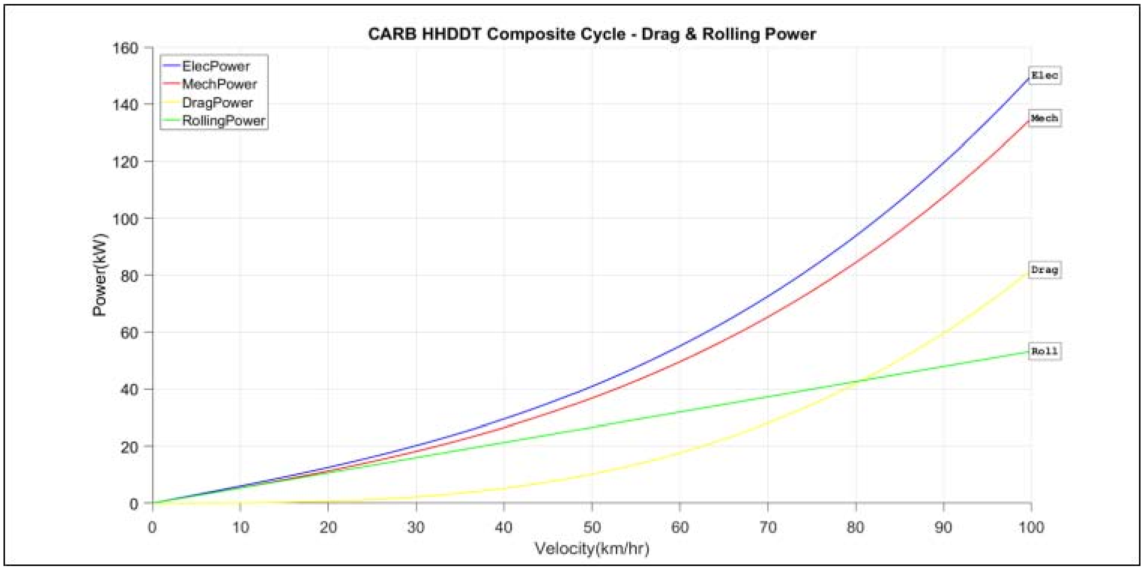

Figure 7 Traction Power Versus Speed

An auxiliary load of 3.5 kW continuous demand, simulating the truck compressor, power steering, lights, etc. was added to the traction motor power. The model also has the capability to cycle loads on/off and add additional auxiliary loads such as hydraulics, cabin heating, and cooling loads, but none were added for this investigation.

An additional variable in the hybrid architecture is the fuel cell control strategy. For this simulation, the fuel cell begins delivering power once the battery SOC (state-of-charge) drops below 70% and the fuel cell power increases as the SOC decreases, reaching full power at 50% SOC. If the fuel cell charges the battery above 80% SOC, the fuel cell is shutdown. Drayage trucks are often required to idle or “creep” for significant periods and, during these periods of low power requirement, the fuel cell is off and the truck would operate on battery power only. Ballard offers the truck integrator the ability to control the fuel cell output, allowing the hybrid control strategy to be optimized for the end-user’s application.

The purpose of the simulation is to identify combinations of fuel cell system output power and battery capacity that meet the application. Combinations of battery and fuel cell which cannot maintain the battery SOC above a healthy minimum are eliminated from further study. The system architecture investigated in this paper is 210 kW fuel cell with 50 kW·h battery system. Referring to the traction power curve in Figure 7, for the peak power requirement of approximately 800 kW the fuel cell can ramp to full power of 210 kW within a few seconds, requiring the battery to deliver the balance of approximately 600 kW. This requires the 50 kW·h battery to be capable of 10C discharge for short periods.

A sample output from the model showing the fuel cell power and the battery SOC for the entire 16 hour simulated duty cycle is shown in Figure 9. The fuel cell maintains the battery SOC within a tight band while the fuel cell power never exceeds ~130 kW output or 62% of rated power. (For an accurate accounting of hydrogen fuel consumption, the simulation runs until the final battery SOC is equivalent to the initial SOC.)

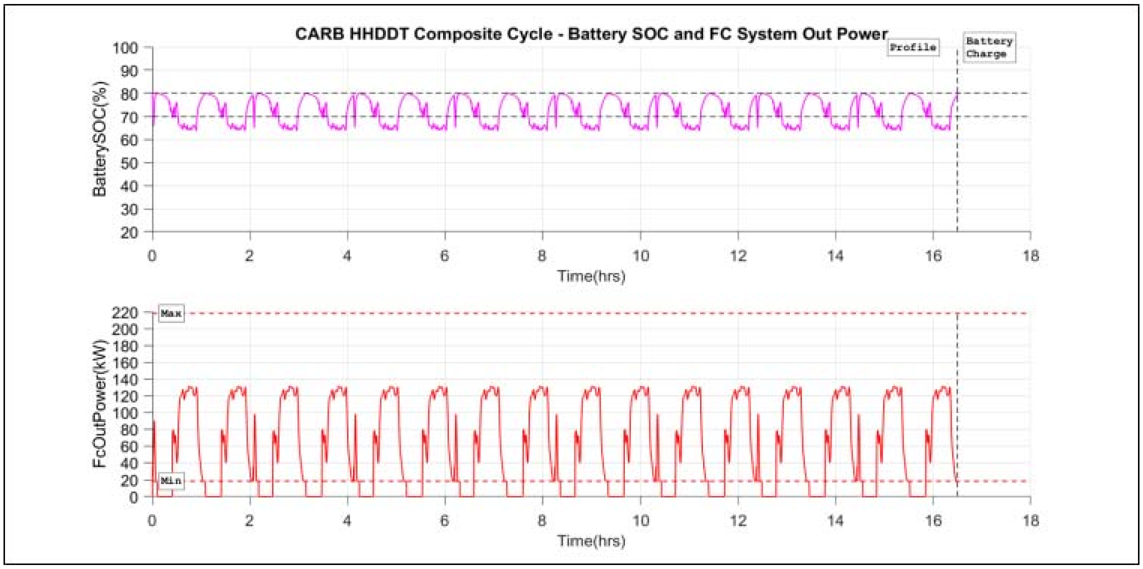

Figure 8 Battery SOC and Fuel Cell Power

Additional output from the model is summarized in Table 4 .

Table 4 Model Results

Model Output	Value
Duration, hours	16.5
Distance, km (miles)	687 (426)
Maximum Speed, km/h (mph)	95 (59)
Average Speed, km/h (mph)	42 (26)
Maximum Acceleration, m/s^2 (ft/s^2)	1.3 (4.3)
Maximum Electric Drive Power, kW	768
Fuel cell maximum net power output, kW	131
Fuel cell mean net power output, kW	62
Battery maximum SOC, %	80
Battery minimum SOC, %	64
Energy delivered to traction motor over duty cycle, kW·h	869
Total energy, including auxiliary power over duty cycle, kW·h	927
Hydrogen consumption, kg	57
Hydrogen consumption, kg / 100 km	8.3

I. Fuel Usage

This simulated 16 hour heavy duty cycle requires approximately 57 kg of hydrogen. In comparison to diesel fuel, the hydrogen consumption rate of 8.3 kg / 100 km is equivalent to 13.7 km/DGE (8.5 mile/DGE).

II. Battery State of Charge (SOC)

During the 16 hour simulation, the battery state of charge was always kept within a range of 64-80%. Although high rates of discharge and charge occur, the battery is never deeply discharged. This beneficial treatment of the battery by the fuel cell is expected to yield long battery life and forego costly battery replacement during the lifetime of the truck.

III. Refueling Time

Heavy duty transit buses are routinely filled with 30 kg or more of hydrogen in 10-15 minutes, and it is therefore expected that refueling the truck with up to 60 kg of hydrogen would be accomplished in approximately 20 minutes or less. This fast refueling is another benefit of the fuel cell truck – 20 minutes refueling is a significant improvement over the hours of charging required for a battery-only truck, increasing truck utilization.

IV. Truck Weight

Using an estimated battery pack weight of 128 Wh/kg and 1.6 kW·h/km[xii], we can estimate that approximately 1100 kW·h of battery are required for this 687 km duty cycle, and that the battery system is approximately 6t (13,200 lbs) heavier than the fuel cell-battery hybrid solution. This negative impact on the allowable payload of the battery truck is a commercial barrier which is readily solved by adopting fuel cell-battery hybrid architecture.

7. AVAILABILITY OF FUEL CELL TRUCKS

Ballard fuel cells for heavy duty transit bus applications have been in commercial use for many years, dating to the mid-1990s. Since 1999, the cost of the fuel cell module has decreased more than 75%, contributing to more than a 50% decrease in total bus cost. Bus costs continue to rapidly decrease as purchase volumes increase.

During this same period, the lifetime of these heavy duty modules has improved over 12 million kilometers of revenue service in 12 countries with challenging climates and duty cycles. Ballard Fuel cell modules operating in London buses have achieved over 27,000 hours of operation without a fuel cell stack replacement.

The success of these heavy duty fuel cell modules is now being extended to trucking and other applications. Ballard has partnered with Kenworth, BAE, CTE and CARB (California Air Resources Board, Zero Emission Cargo Transport II program) to develop and demonstrate a heavy duty, class 8 fuel cell-battery hybrid truck for drayage operation in the San Pedro Bay Ports. It has been noted by Kenworth that improvements in fuel cell power density (power/volume) must be achieved, and that there are significant gains to be made in the integration of the different sub-systems before full commercialization, but the overall impression of the technology is very positive. https://www.youtube.com/watch?v=ShgYjFb4Pp8

8. CONCLUSION

The benefits of a fuel cell-battery hybrid architecture are presented in this paper. Simulation results indicate that a moderately-sized fuel cell module and power-dense battery pack can work effectively together to satisfy the rigorous demands of a drayage duty cycle. A heavy duty truck weighing 32,545 kg (71,600 lbs) was simulated at highway speeds up to 95 km/h (59 mph) and average speed of 42 km/h (26 mph) over a 16 hour drayage duty cycle with periodic accelerations of approximately 0.9 m/s^2 (2.9 ft/s^2) while emitting no harmful tail pipe emissions and consuming about half the energy of a diesel powered truck.

Compared to a truck powered only by batteries, an electric truck powered by a fuel cell-battery hybrid will be high performance, have long range limited only by fuel capacity, carry a 6-ton higher payload , and refuel in minutes. Additionally, the hybrid architecture helps maintain the battery SOC within a healthy range, minimizing damage to the battery thereby enabling increased battery life.

Ballard has available heavy duty fuel cell modules from 30 kW to 100 kW power output and is actively supporting truck integrators and OEMs in developing and demonstrating the next generation of medium and heavy duty zero emission trucks. We welcome you to contact us about our MD and HD fuel cell modules for your projects.

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[i] *The Future of Trucks, Implications for Energy and the Environment; International Energy Agency*

[ii] *Overview of the heavy-duty vehicle market and CO2 emissions in the European Union, 1 Dec 2015, ICCT*

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[iv] *The Future of Trucks, Implications for Energy and the Environment; International Energy Agency*

[v] *The Carbon Footprint of Global Trade, International Transport Forum, OECD/ITF 2015*

[vi] *California Sustainable Freight Action Plan*

[vii] *IEA The Future of Trucks*

[viii] *https://www.statista.com/statistics/253931/global-container-market-demand-growth/*

[ix] *San Pedro Bay Ports Clean Air Action Plan 2017*

[x] *Key Performance Parameters for Drayage Trucks Operating at the Ports of Los Angeles and Long Beach, 15 November 2013, CALSTART*

[xi] *Real-World Activity of Heavy-Duty Tractors Hauling Container Chassis, Flatbed Trailer, and Tank Trailer", Boriboonsomsin, et. al, Center for Environmental Research and Technology, University of California at Riverside*

[xii] *Performance Metrics Required of Next-Generation Batteries to Make a Practical Electric Semi Truck" from ACS Energy Letters, 27 June 2017, American Chemical Society*

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