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TECHNO-ECONOMIC OUTLOOKS FOR THE OPERATION OF ZERO-EMISSION HEAVY-DUTY TRUCKS: THEIR IMPLICATIONS ON FLEET OPERATORS, CARGO SHIPPERS, AND VEHICLE DESIGNERS

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ABSTRACT

Heavy-duty trucking is an essential economic sector and the logistical backbone of the American and global economy. However, heavy-duty vehicles (HDVs) contribute significant CO2 emissions to global warming. HDVs are hard to decarbonize due to the large amount of onboard energy storage required for the range and towing performance needed. Currently, there are two potential promising alternative drivetrain architectures to replace existing diesel fleets: lithium battery-electric vehicle (Li-BEV) and hydrogen fuel-cell-electric vehicle (H2 FCEV). While these alternative-fuel HDVs are on their way toward technical maturity and commercialization, the techno-economic implications of operating a zero-emission fleet remain largely uncertain to stakeholders in the trucking industry. In this study, we developed a multi-dimensional techno-economic model to evaluate the technical constraints of onboard energy storage in HDVs and compare the operational technoeconomics of zero-emission drivetrains against diesel vehicles, using the perspectives of fleet operators and cargo shippers. We have found that although Li-BEV drivetrains show promise in decarbonizing heavy-duty vehicles, they are limited to the short to medium range (<500 mi) and in applications where freight capacity is not a high priority. In the long-haul freight-carrying scenario above 750 miles, H2 FCEVs are shown to be a better candidate for replacing diesel heavy trucks than Li-BEVs, due to a higher cargo capacity. However, to make H2 FCEVs more competitive in the HDV sector, more proactive investments and infrastructure developments are necessary to establish a mature hydrogen supply chain and to further reduce the price of hydrogen fuel to 2 $USD/kgH2$. It is also apparent that the operational techno-economics and freight performance of the zero-emission options remain out-competed by existing diesel fleets. Governments would need to put forth aggressive fiscal and regulatory policies to promote the competitiveness of zero-emission drivetrains and limit the use of diesel vehicles.

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1. INTRODUCTION

Since 1850, greenhouse gas emissions from human activities have led the global mean surface temperature to rise 1.1°C with a projection of exceeding 1.5°C over the next 20 years [1]. Among various sources of greenhouse gas emissions, the transportation sector accounts for 27% of global emissions, making it the second-largest contributor to CO2 emissions [2]. Heavy-duty trucks (HDVs) are the crucial backbone of the global supply chain and its economy, due to a heavy reliance on using land-based infrastructure to transport goods to and from international ports and distribute them domestically. In the United States alone, there are approximately 2.9 million registered heavy-duty semi-trucks and they transport around 80% of all domestic freight [3, 4]. The heavy-duty trucking industry consumes a total of 29 billion gallons of diesel and emits 810,000 tons of CO2 annually, which is equivalent to 6% of the US's annual greenhouse gas emissions [5, 6].

To address CO2 emissions from heavy-duty commercial vehicles, many nations around the globe have set forth strategic policies and regulatory targets to promote the adoption of zero-emission trucks and buses [7]. Currently, lithium-battery-based electric (BEV) and hydrogen-based fuel-cell-electric (FCEV) vehicles are two of the most promising zero-emission alternatives considering both technical and economic conditions [8, 9]. The United States invested 1 billion USD to support the transition to zero-emission HDVs through the Inflation Reduction Act of 2022 and proposed stricter CO2 standards for HDVs by 2027 [10]. The European Commission has proposed to reduce 90% of the carbon emissions from its HDVs by 2040 and reach carbon neutrality by 2050 [11]. The Chinese Government has also initiated its *Action Plan for the Battle Against Diesel Truck Pollution* to promote cleaner diesel trucks and the adoption of alternative fuel vehicles [12]. In addition to fiscal policy and emission regulation, the

US Department of Energy has tasked industry stakeholders directly through its SuperTruck initiatives to develop technologies that enhance the efficiency of existing diesel trucks and develop zero-emissions HDV prototypes [13]. Aside from governmental efforts, automotive companies such as Volvo, Tesla, Peterbilt, and Freightliner are developing first-generation BEV class-8 trucks [14–17], while Hyundai, Toyota-Kentworth, Daimler, and Nikola are pushing toward FCEV platforms [18–21].

However, the wide-scale adoption of zero-emission heavy-duty trucks is hindered by various technical and socioeconomic challenges. Unlike light-duty vehicles (LDVs), heavy-duty commercial vehicles are harder to decarbonize and electrify. Over the past decade, there has been rapid adoption of zero-emission drivetrains in the LDV space. In 2021, 8.57% of the market share in global vehicle sales are electric vehicles, with 99% of them being BEVs [22, 23]. The primary driving forces behind the rapid popularization of BEVs in the LDV sector are the commercial maturity of lithium battery technologies lowering the costs of energy storage, the readily available access to grid electric infrastructure for recharging, and tax incentives from government policies. Nonetheless, the solution of decarbonizing HDVs may not be as simple as scaling up the BEV platform from LDV to the HDV form factor. Long-haul HDVs such as Class-8 semi-trucks require a large amount of onboard energy storage and power output to meet the towing performance required (up to 80,000 lbs) over a long distance (>500 mi). Moreover, unlike passenger vehicles, a long-haul commercial vehicle also needs to be designed considering the freight performance and the driver's living conditions, which poses additional techno-economic uncertainties when transitioning from existing diesel drivetrains to alternative energy drivetrains.

Based on interactions with stakeholders such as refueling network providers, automotive manufacturers, and existing fleet owners, it seems apparent that the heavy trucking industry is relatively risk-averse and the green transition of the HDV ecosystem is slow-paced. Currently, there are three primary barriers to the adoption of zero-emission HDVs.

The first barrier is the lack of adequate heavy-duty refueling and recharging network infrastructure. For Li-BEVs, high-power recharging stations specifically designed for HDVs, such as Tesla's 750kW Megacharger, remain relatively scarce [24]. Even with the installation of these high-power chargers, the charging time of the Li-BEVs remains a significant concern to fleet operators, as it would take over one hour to fully charge a 500-mi range electric vehicle in contrast to a 15-20 minutes refueling time of a 2000-mi range diesel truck. Moreover, a significant upgrade to the existing electric grid infrastructure is likely required to support the large-scale deployment and simultaneous operation of these high-power chargers, posing further roadblocks to adoption. For FCEVs, the supply network of hydrogen from production sites to refueling sites remains immature, and the availability of hydrogen refueling stations is even more scarce and limited to LDV FCEV capacity. Without a clear guarantee of long-term return on investment, infrastructure suppliers remain reluctant to expand investment in alternative refueling stations without a significant market share of zero-emission HDVs in operation, and with sufficient government incentives.

Secondly, the high capital cost (CAPEX) of zero-emission vehicles due to low manufacturing volume and the lack of technical maturity poses another adoption barrier for fleet owners. Currently, many zero-emissions HDVs remain in the prototype and early commercialization phase, while automotive OEMS lack the amount of volume demand in the HDV markets to enter mass production and reach an economy of scale. These first-generation test-pilot vehicles are often designed by incorporating existing off-the-shelf technologies into a system-level package that can meet HDV performance with a medium range of around 500 miles. Without the driving force of an appreciable market demand for zero-emissions vehicles and the maturity of sub-system level technologies specifically designed for HDVs, it may hinder large vehicle OEMs' process to further invest and develop further generations of mass-adoption ready vehicle designs across the various range requirements and application.

Finally, as the potential first adopters of zero-emission HDVs, commercial fleet owners are likely hesitant to convert existing diesel fleets toward zero-emission alternatives, as the implicated effects of the transition on their business case remain uncertain. As the government mandates stricter emission regulations towards diesel vehicles and imposes the adoption of carbon-neutral vehicles, fleet owners will likely face uncertainties in the availability and reliability of the refueling infrastructure of alternative fuels, the high capital costs of the zero-emission vehicles, as well as the techno-economic uncertainty of operating a zero-emission fleet. Moreover, while fleet owners can be operating with a profit margin as low as 10%, they may find themselves in a dilemma between maintaining a profitable business, accelerating government regulation, technical readiness of zero-emission vehicles, and the economic viability of alternative fuels. This results in a vicious cycle where the stakeholders are all waiting for each other to make the first move.

As the future roadmap of adoption remains largely uncertain to fleet operators and other stakeholders in the HDV ecosystem, it may be beneficial to elucidate the techno-economic outlooks when operating a zero-emission fleet. Cunanan et al. conducted a thorough review comparing the drivetrain technical performance of diesel internal-combustion engines (ICE), BEVs, and hydrogen FCEVs, and discussed their recent technological developments [25]. Jones et al. have investigated the realistic long-haul drive cycle of existing heavy-duty diesel trucks and provided a more accurate simulated benchmark for fuel consumption, carbon emissions, and total costs to society [26]. On the fuel supply side, researchers have also analyzed the techno-economic cases of the hydrogen supply chain. Rong et al. identified the optimal transportation modes of hydrogen between the production site and fueling station for various distances and volume demands [27]. Reddi et al. quantified the sensitivity of hydrogen station configurations on the cost of refueling, [28]. Muratori et al. conducted a deep investigation into the current state of the fast charging network for BEVs and its techno-economic implications based on different usage scenarios and electricity pricing structure [29]. Moreover, many scholars across higher institutions and government agencies have studied the techno-economic feasibility of decarbonizing existing diesel fleets with BEVs or FCEVs, ranging from reviewing the existing techno-economic roadblocks for alternative energy vehicles, quantifying the techno-economic feasibility for battery-electric heavy-trucks in different parts of the world, elucidating the long-term perspective of using LOHC in HDVs, to proposing technical targets that make decarbonizing HDVs viable [30–39]. In particular, Mauler et al. have developed a comprehensive modeling framework to simulate the total cost of ownership comparing diesel, lithium-BEV, Nickel-BEV, and FCEV, recommending the most cost-effective strategy for the different usage scenarios [40]. While these prior arts contribute further understanding of the various techno-economic tradeoffs between different zero-emission drivetrains and existing diesel fleets, the relationship between the vehicle design and the operational techno-economic interests of the fleet operators has yet to be explicitly explored. In this study, the techno-economic relationship and sensitivity between the vehicle design range, the required energy storage, the operational cost of energy/fuel, and the cargo revenue from distance-based and weight-distance-based rates are explored and quantified. The outcome of the study is to help fleet operators and vehicle OEMs to further understand how the design of the vehicle can affect the operational techno-economics of the freight, for the different zero-emission drivetrains, while comparing against existing diesel trucks as a benchmark.

2. PROBLEM FORMULATION

In this work, we create a multi-variable model to understand the techno-economic implications of diesel ICE, Li-BEV, and H2 FCEV drivetrains from the perspectives of fleet operators and shippers. The framework of the model is illustrated using the flow chart shown in Figure 1. The model accounts for parameters relating to the energy carrier, the drivetrain, and the techno-economics of the freight; modules for each of these elements are discussed in further detail in this section. Three sensitivity input variables are investigated in this study: the cost of energy, the maximum range of the vehicle, and the cargo pricing structure utilized by the fleet operators. The fixed parameters in this study, including the properties of the energy carrier, the vehicle drivetrain specifications, and cargo pricing, are listed in Table 1.

The per-unit cost of the energy (c_{energy}) is examined as a set of two discrete values, one representing higher energy costs and one representing lower energy costs, for each of the three drivetrain architectures. Historical U.S. transportation data have shown that the cost of diesel fuel over the past decade fluctuated between 2.2 USD/gal and 4.2 USD/gal (0.054 - 0.103 USD/kWh) [31, 41]. Studies have found that the energy costs of electricity in the U.S. can range from 0.05 USD/kWh to 0.25 USD/kWh depending on the geographical location of the charging station [29]. Given its nascency, the refueling of hydrogen currently can cost as much as 15 $USD/kgH2$ (0.45 USD/kWh) with a projected future price of around 2 $USD/kgH2$ (0.06 USD/kWh) in a mature FCEV market according to the Department of Energy [42].

The design range of the vehicle (D) is set as a continuous design variable ranging from 100 miles to 2000 miles on a single trip without recharging or refueling. In a typical Class-8 HDV, two outrigger diesel tanks, one on each side of the cab, can hold up a total of 300 gallons of diesel and provide up to a 2000-mile range. However, from an operational standpoint, federal regulation limits a property-carrying driver from driving more than 11 hours per day [43]. In addition, historical data and recent studies have shown that the realistic drive cycle of a long-haul class-8 vehicle has an average driving speed of 40-60 mph covering a daily range of 550-750 miles [26]. Therefore, it is logical to assume the realistic design range for a long-haul HDV in a single-day operation is around 500-750 miles for a single driver and 1000-1500 miles for a two-driver team.

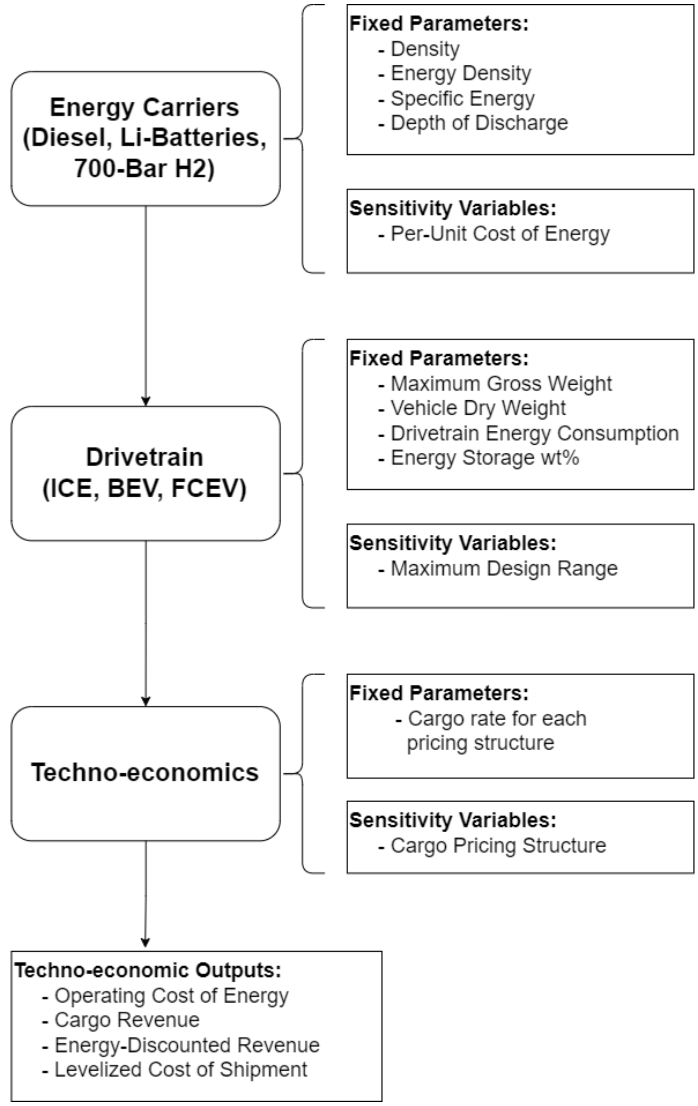


FIGURE 1: Techno-economic Model Flow Chart

Lastly, two types of cargo pricing structures are examined: distance-based flat-rate pricing and weight-adjusted-distance pricing. These two pricing structures can lead to two different techno-economic prospects for fleet owners and shippers when transitioning to the operation of zero-emission HDVs. The distance-based flat-rate pricing structure is often used by fleet operators in a full-truckload cargo scenario, in which a single shipper will fill up the entire trailer and maximize the amount of cargo by weight and/or volume. In this scenario, the fleet operators charge the shipper a flat USD/mi rate (c_{cargo}^{flat}) regardless of the shipment weight or volume. On the contrary, a fleet operator may also compile multiple fractional-truckload cargoes from several shippers into a single trailer, charging each of them a weight-adjusted-distance rate (c^{wt}_{cargo}) of $USD/ton\text{-}mi$. Currently, the national average for flat-rate shipment is approximately 2.5 USD/mi while the weight-adjusted rate is reported to be 0.24 $USD/ton\text{-}mi$ (US ton) [44, 45].

2.1 Energy Carrier Module

Diesel fuel, lithium batteries, and 700-bar compressed gaseous hydrogen are the energy carriers modeled in this study. Diesel fuel has been the standard fuel used in HDVs and large equipment over the past several decades. As a hydrocarbon-based fuel, it is refined from crude oil and distributed through the well-established supply infrastructure around the globe. Diesel has an approximate lower heating value of 128,488 Btu/gal (9,948 kWh/m^3) and a density of 7 lb/gal (840 kg/m^3), giving it a specific energy of 18,355 BTU/lb (11.8 kWh/kg) [46].

On the other hand, although lithium batteries are a mature and vastly commercialized technology, they remain an active area of research and development, and there have been continuous improvements in energy density, discharge capacity, degradation, thermal runaway, and efficiency. The latest lithium battery cells that are currently deployed in commercially available BEVs have a specific energy of 170 Wh/kg. The battery pack composed of these cells is shown to have a specific energy of 140 Wh/kg and an energy density of 332 Wh/L [47].

Alternatively, hydrogen used in FCEVs can be stored onboard using compression or liquefaction, or through a material-based method using chemical bonds [48]. Currently, most refueling stations and commercially available FCEV designs use 350-bar and 700-bar hydrogen due to the relatively simple compression process to increase storage energy density, and it has a lower energy loss in the process than liquefaction. Studies have shown that compressing hydrogen up to 700 bar requires around 10% of its lower heating value while liquefaction consumes over 30% [49]. This study focuses on modeling 700-bar hydrogen for FCEV since it is the most common pressure found amongst commercial HDV deployment in California. Compressed hydrogen at 700 bar has a density of 39.4 kg/m^3 at 25 $°C$, leading to a specific energy of 33.3 kWh/kg (120 MJ/kg) and an energy density of 1310 kWh/m^3 (LHV) [50, 51].

In addition, the maximum depth of discharge (DoD) is incorporated for each of the three energy carriers, which represents the actual amount of energy stored within the energy carrier that is usable to generate power for the drivetrain. For diesel, the entire diesel tank can be withdrawn therefore it has a DoD of 100%. However, lithium batteries generally have a DoD of 80% to protect the cell's longevity; and only 90% of compressed hydrogen is assumed to be usable gas with 10% remaining as cushion gas in the storage tank.

2.2 Drivetrain Module

The onboard energy storage required can be calculated given the energy consumption of the drivetrain and the maximum design range. The weight (W_{energy}) and volume (V_{energy}) of the energy carrier are calculated using the linear relationship defined in Eq. 1 and Eq. 2, respectively, for each of the three drivetrain architectures. The variables η_{DT}, e_i, u_i, and DoD_i correspond to the energy consumption of the drivetrain, the specific energy, the energy density, and the depth of discharge of the energy carrier, respectively.

$$W_{energy} = \frac{D}{\eta_{DT} \cdot e_i \cdot DoD_i} \tag{1}$$

$$V_{energy} = \frac{D}{\eta_{DT} \cdot u_i \cdot DoD_i} \tag{2}$$

Studies have reported that a typical Class-8 truck running on a diesel ICE drivetrain has a fuel consumption rate ranging from 6 to 10.8 mi/gal, with an approximate average fuel efficiency of 6.5 mi/gal [25, 31, 39]. Conversely, commercial models of Li-BEVs HDV were found to have an energy efficiency ranging from 0.43 to 0.6 mi/kWh depending on road and load conditions, with the energy efficiency of the production-ready Tesla Semi reported to be around 0.5 mi/kWh [15, 25, 31, 36]. Moreover, while HDVs using H2 FCEV drivetrain remain the least-established platform compared to diesel and Li-BEV, scholars have predicted the early pilot models of H2 FCEV HDVs have a fuel economy range of 5.5 to 9.4 $mi/kgH2$. In this study, the energy consumption for diesel ICE, Li-BEV, and H2 FCEV are assumed to be 0.16 mi/kWh (6.5 mi/gal), 0.5 mi/kWh, and 0.27 mi/kWh (9 $mi/kgH2$), respectively.

The available cargo weight capacity (W_{cargo}) is calculated using Eq. 3 as the remaining gross weight after considering the vehicle's dry weight (W_{dry}) and the weight of the energy storage ($W_{storage}$). The maximum gross weight (W_{gross}) of a class-8 HDV is 80,000 lb (36,300 kg) and is mandated by law in the majority of States [52]. The dry weight of the vehicle is assumed to be 27,000 lb (12,250 kg) for all three drivetrains, which accounts for the unloaded weight of the truck excluding the energy storage. This simplified dry weight parameter may include components such as the ladder-frame chassis structure, the drivetrain, the transmission, the wheel assembly, the empty weight of the trailer, and any auxiliary systems.

$$W_{cargo} = W_{gross} - W_{dry} - W_{storage} \tag{3}$$

The weight of the energy storage is calculated by dividing the weight of the energy carrier by the weight percentage of the energy storage unit ($wt\%_{storage}$) using Eq. 4. For a diesel ICE, an empty 150-gallon diesel fuel tank weighs approximately 200 lb, resulting in a wt% of around 84% [53]. The wt% of the lithium battery is assumed to be 100% since the weight of the battery structure is already accounted for in the specific energy of the battery pack. In H2 FCEV, a commercially available Type IV composite hydrogen storage tank for 700-bar compressed hydrogen generally has a wt% between 4 - 6, and a 5.7 $wt\%$ is used in this study based on the specifications of the storage tank deployed in a Toyota Mirai [54, 55]. In addition, a heavy metal rack is typically built around the stack of hydrogen composite tanks on current heavy-duty HDV designs to protect the pressure vessels from external impact. From stakeholder interviews with automotive manufacturers, this metal rack structure in FCEVs can weigh as much as the hydrogen storage tanks, reducing the weight efficiency of the energy storage by approximately 50%.

TABLE 1: Table of Model Parameters (* indicates sensitivity variables)

Model Parameters	Diesel ICE	Li BEV	H2 FCEV
Energy Parameters			
Density (ρ)	840 kg/m^3	2370 kg/m^3	39.4 kg/m^3
Energy Density (u)	9,948 kWh/m^3	332 kWh/m^3	1310 kWh/m^3
Specific Energy (e)	11.8 kWh/kg	0.14 kWh/kg	33.3 kWh/kg
Depth of Discharge (DoD)	100%	80%	90%
Drivetrain Parameters			
Max. Design Range* (D)		100 mi - 2000 mi	
Max. Vehicle Gross Weight (W_{gross})		36,300 kg (80,000 lb)	
Vehicle Dry Weight (W_{dry})		12,250 kg (27,000 lb)	
Energy Consumption (η_{DT})	0.16 mi/kWh	0.5 mi/kWh	0.27 mi/kWh
Energy Storage Weight Perct. ($wt\%$)	84 $wt\%$	100 $wt\%$	5.7 $wt\%$ (tank) 50 $wt\%$ (rack)
Techno-economic Parameters			
Cost of Energy* (Low) (c_{energy})	0.054 USD/kWh	0.05 USD/kWh	0.06 USD/kWh
Cost of Energy* (High) (c_{energy})	0.103 USD/kWh	0.25 USD/kWh	0.47 USD/kWh
Cargo Rate for Distance-Based Pricing* (c_{cargo}^{flat})		2.5 USD/mi	
Cargo Rate for Weight-Distance-Based Pricing* (c_{cargo}^{wt})		0.24 $USD/ton\text{-}mi$ (US Ton)	

Therefore, the aggregate wt% for hydrogen storage used in this study is 2.85 wt%.

$$W_{storage} = \frac{W_{energy}}{wt\%_{storage}} \tag{4}$$

2.3 Techno-economic Module

Using the properties of the energy carrier and the respective drivetrain performance, we can simulate the techno-economic impacts on the fleet operators and shippers when operating these different drivetrain architectures. Four techno-economic metrics are considered:

- Operational cost of energy: C_{energy}^{tot}
- Cargo revenue: R_{cargo}
- Energy discounted operational revenue: R_{dct}
- Levelized cost of shipment: C_{shpmt}

These operation metrics are evaluated on a per-trip basis, meaning the vehicle transported the cargo over its assigned range without refueling or recharging. Eq. 5 calculates the total operational cost of energy based on the per-unit cost of energy, drivetrain energy consumption, and the vehicle range.

$$C_{energy}^{tot} = \frac{D \cdot c_{energy}}{\eta_{DT} \cdot DoD_i} \tag{5}$$

The cargo revenue received by the fleet operators for transporting the freight can be calculated using Eq. 6 and 7 for the distance-based flat rate pricing and the weight-adjusted-distance pricing, respectively.

$$R_{cargo}^{flat} = D \cdot c_{cargo}^{flat} \tag{6}$$

$$R_{cargo}^{wt} = D \cdot c_{cargo}^{wt} \cdot W_{cargo} \tag{7}$$

The energy-discounted operational revenue earned by the fleet operators can be calculated as the difference between the cargo revenue and the total energy cost (Eq. 8).

$$R_{dct} = R_{cargo} - C_{energy}^{tot} \tag{8}$$

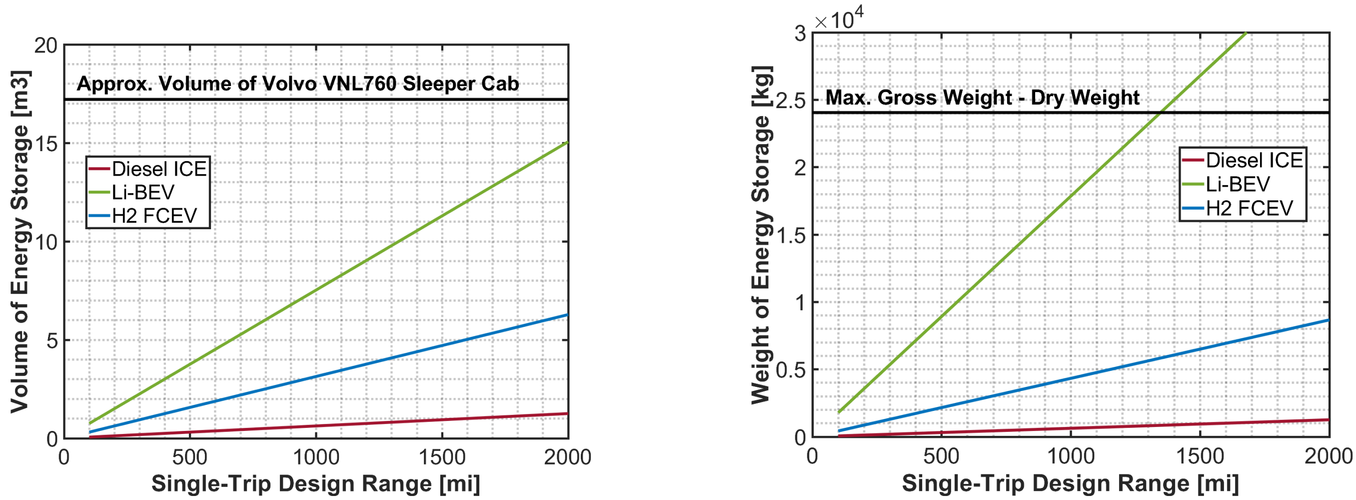
Lastly, a shipper may use the levelized cost of shipment as a metric to quantify how much money they need to spend to ship a unit weight of cargo over a fixed distance. Eq. 9 calculates the levelized cost of shipment paid by the shipper, which is the cargo revenue (or cargo cost in the shipper's perspective) normalized by the cargo weight.

$$C_{shpmt} = \frac{R_{cargo}}{W_{cargo}} \tag{9}$$

3. SIMULATED TECHNO-ECONOMIC OUTLOOKS

3.1 Onboard Energy Storage Required

The volume and weight of the required onboard energy storage for diesel ICE, Li-BEV, and H2 FCEV are respectively shown in Figure 2a and Figure 2b, as a function of the maximum design range. In Figure 2a, the approximated volume footprint of a Volvo VNL760 sleeper cab is also plotted as the horizontal line, representing the total amount of volumetric space in a typical long-haul truck with a 70" sleeper. It is calculated by approximating the sleeper cab as a triangular boss using the manufacturer's dimension specification (89.4" W x 197.8 L x 123.7 H) [56]. As shown in Figure 2a, lithium batteries in a Li-BEV drivetrain can take up a significant portion of available space in the sleeper cab as the design range of the vehicle increases, while 700-bar compressed hydrogen takes up less than half as much. In comparison, conventional diesel fuel remains the most volumetrically dense energy



(a) Volume of Energy Storage **(b) Weight of Energy Storage**

FIGURE 2: Volume and Weight of Energy Storage Required Onboard as a Function of the Maximum Design Range for Diesel ICE, Li-BEV, and H2 FCEV drivetrains.

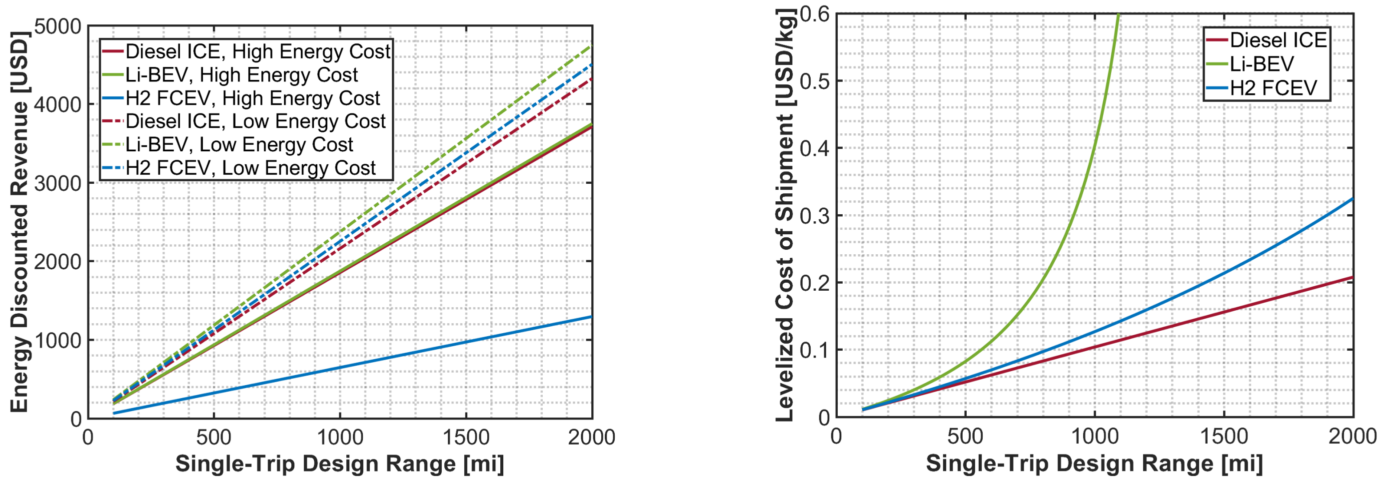
carrier. When designing a long-haul HDV with a 1200-mi range, it is apparent that the energy storage in a Li-BEV will take up close to 50% of the sleeper cab volume, with H2 FCEV and diesel ICE only occupying 25% and 5% respectively. It is important to note that although Figure 2a shows there is sufficient space in a typical sleeper cab to house the total volume of energy storage for any drivetrain up to 2000 miles, a large proportion of the cab volume will be allocated to the driver's cabin, sleeper compartment, and the drivetrain compartment. In reality, the total volume of energy carriers that can be stored *only* within the footprint of the vehicle cab can be rather limited.

In Figure 2b, the horizontal line represents the remaining weight capacity in a Class-8 HDV that can be attributed to energy storage and cargo, after subtracting the vehicle dry weight from the maximum gross weight limit. The limitation of Li-BEV drivetrains in long-haul HDV is evident when considering the weight of the energy storage. As shown in the figure, a Li-BEV HDV will have zero cargo weight capacity and exceed the maximum weight limit when it is designed with a range above 1300 miles. Even when designing a mid-range HDV with a range of 500 mi, lithium batteries will take up close to 38% of the remaining weight capacity, leaving only 62% to cargo capacity. On the contrary, an H2 FCEV with a 500-mi range will have a cargo weight capacity of approximately 90% and over 75% when designed for 1300-mi. Although there is interest in phasing out diesel fuels in Class-8 trucks, it remains the highest gravimetrically energy-dense option for long-haul HDV, accounting for only 5% of the remaining vehicle weight capacity, even with a 2000-mi range.

3.2 Flat-Rate Distance-Based Cargo Pricing

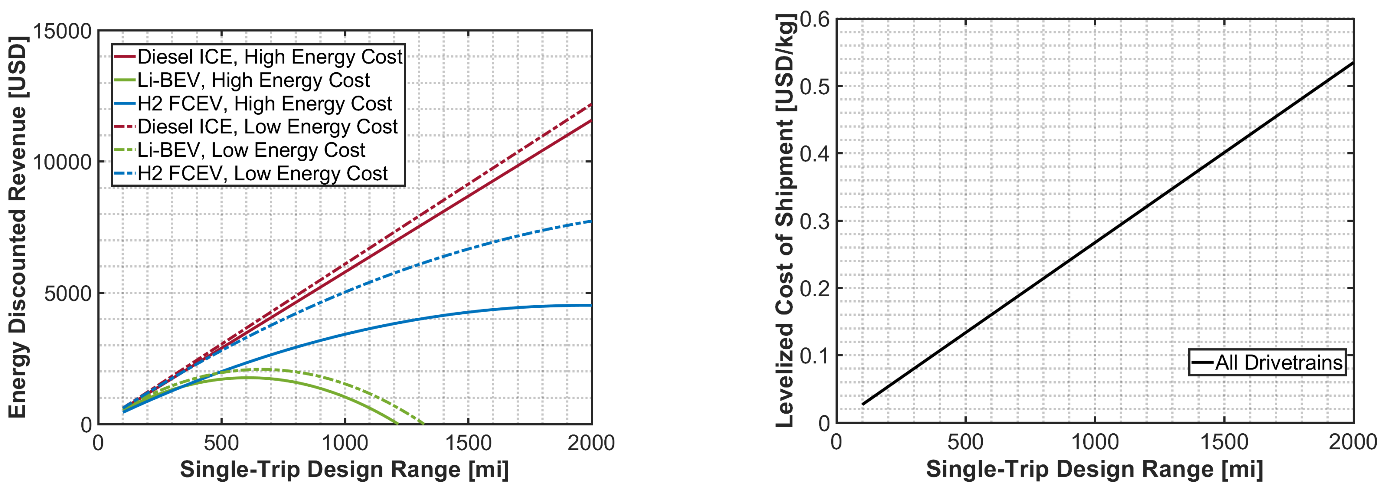
Figure 3 shows our techno-economic analysis of the operation of a flat-rate distance-based pricing structure, where the fleet operator charges the shipper a fixed 2.5 USD/mi distance rate for the cargo shipment. Figure 3a shows the net cargo revenue received by the fleet operator after discounting the total cost of energy that was used by the freight over the shipment range. Based on these results, when the per-unit cost of energy is comparable between diesel, BEV, and FCEV in the low-energy cost scenario, the fleet operator will make more revenue when operating a more efficient drivetrain (BEV > FCEV > diesel). Furthermore, in the high energy cost scenario, the energy-discounted operational revenue is even more sensitive to the drivetrain efficiency. For example, an operator driving a Li-BEV HDV may make the same amount of operational revenue as a conventional diesel truck even when the per unit cost of electricity (0.25 USD/kWh) is more than twice the cost of diesel fuel (0.103 USD/kWh). Moreover, with the current high cost of H2 at 15 $USD/kgH2$, it is shown that H2 FCEV has yet to reach parity with diesel or Li-BEV from an operational cost of energy perspective. Therefore, for H2 FCEV to be more economically favorable to the fleet operators from their operational standpoint, the current cost of H2 must go down to approximately 2 $USD/kgH2$ to compete with diesel and electricity prices.

While Figure 3a demonstrates that operating a Li-BEV drivetrain can be economically attractive to the fleet owner under a flat cargo rate, Figure 3b narrates a different economic viewpoint from the shipper's perspective. Figure 3b shows the levelized cost of shipment as a function of the vehicle range for the three modeled drivetrains. As shown in Figure 3b, although Li-BEV is highly efficient, the levelized cost of shipment using a Li-BEV truck also skyrockets for long-haul freight above 500 miles when operating using the flat-rate pricing structure. This is because of the large weight penalty of lithium batteries onboard a long-haul truck due to its low specific energy (as shown in Figure 2b), drastically reducing the Li-BEV's cargo capacity available to the shipper over a long distance. In comparison, a long-haul HDV using an H2 FCEV or a diesel ICE drivetrain will have a lower levelized cost of shipment, due to their high fuel gravimetric energy density leading to more cargo weight capacity in the trailer. As a result, a shipper may be more economically incentivized to use a traditional diesel truck or an H2 FCEV under the flat-rate



(a) Energy Discounted Operational Revenue **(b) Levelized Cost of Shipment**

FIGURE 3: Energy discounted operational revenue for fleet operators using a flat-rate distance-based pricing structure (2.5 USD/mi), and the associated levelized cost of shipment to the shipper.



(a) Energy Discounted Operational Revenue **(b) Levelized Cost of Shipment**

FIGURE 4: Energy discounted operational revenue for fleet operators using a weight-adjusted-distance pricing structure (0.24 $USD/ton\text{-}mi$), and the associated levelized cost of shipment to the shipper.

pricing structure, as they can transport more cargo for the same cost.

3.3 Weight-Adjusted-Distance Cargo Pricing

The techno-economic outlooks in a freighting operation using a weight-adjusted-distance rate of 0.24 $USD/ton\text{-}mi$ are shown in Figure 4. As shown in Figure 4a, the energy-discounted operational revenue is highest when the fleet owners operate diesel trucks, followed by H2 FCEV, with Li-BEV generating the lowest revenue. The limitation of operating long-haul Li-BEV is apparent in this Figure, where the energy-discounted revenue of Li-BEV starts to diminish beyond the 500-mi range, and approaches net-zero above the 1200-mi range. Since the majority of weight capacity in Li-BEV is attributed to the lithium batteries in long distances, it lacks the cargo weight capacity to generate sufficient revenue that outweighs the cost of energy during vehicle operation. On the other hand, H2 FCEV with a futuristic low hydrogen cost of 2 $USD/kgH2$ is shown to reach revenue parity with diesel trucks below the 500-mi range, while diesel continues to outcompete in the long-haul greater than 500 miles. However, at the current high price of hydrogen, an H2 FCEV may even underperform Li-BEV in the <500-mi range and only generate half as much revenue as a diesel truck, while showing a trend of diminishing revenue above 1700 miles. Furthermore, the per-unit-weight cost of cargo remains constant to the shipper for all drivetrains under the weight-adjusted-distance pricing structure as shown in Figure 4b.

4. DISCUSSION

4.1 Implications on Vehicle Design and Infrastructure

When considering zero-emissions alternatives to decarbonize HDVs, one of the fundamental design challenges is to store sufficient energy onboard given the volume constraint in the tractor cab and the potential weight penalty that reduces cargo capacity. As shown in Table 1, both zero-emission alternatives have their advantages and disadvantages when compared to conventional diesel fuels.

Hydrogen as an energy carrier has a gravimetric energy density that is three times that of diesel and over 200 times that of lithium batteries. However, even when compressed to 700 bar, the volumetric energy density of hydrogen is still one-seventh that of diesel fuel. At the same time, diesel fuel is also 30 times as volumetrically energy-dense as lithium batteries. Moreover, when accounting for 2.85 wt% of the hydrogen storage tank and rack, the gravimetric energy density of onboard hydrogen storage reduces to one-tenth that of diesel fuel and ten times that of Li-Batteries. This makes the design of the onboard hydrogen storage system highly crucial to the successful adoption of H2 FCEV in the HDV market, especially since the weight advantage is one of the prominent value propositions that hydrogen has over other alternative fuel options.

Li-BEV drivetrains have the highest energy efficiency, making them twice as efficient as H2 FCEV and three times as efficient as existing diesel fleets. The high efficiency of Li-BEV drivetrains makes them ideal zero-emission alternatives for short- and medium-range freight operations that involve large amounts of city driving. However, lithium batteries as an onboard energy storage underperform both conventional diesel and hydrogen in terms of weight and volume. The low gravimetric and volumetric energy densities of lithium batteries make them less suitable for freight applications where the gross weight of the vehicle and the cargo space available are constrained. As shown in Figure 2b, the range of a Li-BEV HDV can be inherently limited by the weight of the lithium batteries themselves, making them only viable in the sub-medium range below 500 miles. These shorter-range vehicles are less sensitive to the weight penalty of lithium batteries since they do not require as large an amount of onboard energy storage as long-haul vehicles and do not require as much cargo capacity. The reality of limitations in HDVs using Li-BEV drivetrain is reflected in the Tesla SEMI, in which the highest range variant is only 500 mi with an unofficial estimate of a battery pack weighing around 11,000 lbs [57].

Moreover, Li-BEV HDVs may also face technical issues related to recharging infrastructure. For example, a 500-mi range Li-BEV HDV will need over an hour to fully recharge using a 750kW high-power charger [58]. This means Li-BEV HDVs will need a sizable amount of downtime for recharging, which reduces the vehicle's potential travel time and limits its freight operation to surround a central hub. In addition, with multiple high-power chargers running simultaneously to recharge a fleet of heavy-duty BEVs, the electric grid infrastructure may face extraordinary strain and a significant upgrade to the grid infrastructure may be needed to maintain its stability.

In the long haul category (>750 mi), the H2 FCEV drivetrain may be more suitable to replace existing diesel fleets than BEVs, as shown in Figure 2. H2 FCEVs require less weight and volume for onboard energy storage and provide higher cargo capacity than BEVs, leading to more revenue generation for the fleet operators and lower levelized costs of shipment to the shipper. Moreover, hydrogen can be refueled within a relatively short timeframe, similar to conventional diesel [25], eliminating the wait time needed for recharging in Li-BEVs. However, the existing supply network of hydrogen fuel has yet to reach maturity, continued investment and development from governments and corporations are needed to reduce the current price of hydrogen and ensure a stable fuel supply during the transition to zero-emission fleets.

In the effort to design the next generation of HDVs with zero-emission drivetrains, vehicle manufacturers may want to consider incorporating both Li-BEV and H2 FCEV technologies for different range requirements, cargo capacity, and freight applications. For a vehicle in the short and medium range (<500 mi) that involves a large amount of city driving and is not sensitive to the cargo capacity, leveraging the matured technologies and more established infrastructure of the Li-BEV drivetrain can be promising to decarbonize the corresponding diesel fleet. For example, vehicles such as a hub-to-spoke day cab, a service/utility truck, or a mail delivery truck can be potentially decarbonized with Li-BEVs with reasonable economic feasibility. On the other hand, when designing an HDV for the long-haul market (>750 mi) where the freight capacity is crucial to the function of the vehicle, such as a hub-to-hub sleeper cab, H2 FCEVs can be a potential candidate for substitution.

4.2 Implications on Operational Techno-economics

The quantified energy-discounted revenue and levelized cost of shipment have shown that the drivetrain architecture will have different implications on the operational techno-economics of the fleet operators and the shipper, depending on the cargo pricing structure. In the case of flat-rate distance pricing, Figure 3 shows that shippers are more sensitive to the operational freight performance of the drivetrain than the fleet operators. The weight of the onboard energy storage required of a specific drivetrain directly affects the total amount of freight that a shipper can move over a certain distance. As shown in Figure 3, the levelized cost of shipment for a shipper is highly sensitive to the energy density. This represents an intrinsic value incentive in a free market where the shipper will always be in favor of a drivetrain that allows for higher cargo capacity, such as using an H2 FCEV over a Li-BEV.

On the other hand, the operational revenue to the fleet operators (Figure 3a) is mainly affected by the combination of the fuel price and the drivetrain efficiency. In other words, fleet operators under the flat-rate pricing structure are more economically concerned with the energetic performance of the drivetrain during operation than its impact on the cargo capacity of the truck. This renders the fleet operators less sensitive to the choice of the drivetrain from an operations perspective.

In contrast, the sensitivity to drivetrain architecture shifts completely towards the fleet operators under the weight-based pricing structure. The operational revenue of fleet operators is highly susceptible to the weight of the energy storage on the vehicle. As the example in Figure 4a demonstrates, although an H2 FCEV may incur a higher operational cost of energy due to a high hydrogen price, it can still lead to a higher operational revenue potential due to a larger cargo capacity that can be used to generate revenue. From this perspective, fleet operators will likely prefer a drivetrain architecture that will allow them to haul more cargo over a longer distance, to maximize the revenue they can generate over the lifetime of the freight vehicle. Conversely, since the levelized cost of shipment remains constant for the shippers in this pricing structure, they are likely to be indifferent about the types of drivetrain used by the fleet operators to deliver their shipment.

4.3 Implications on Policy and Regulation

Similar to the electrification in the LDV sector, government policies and regulations are likely necessary to reduce diesel reliance in the HDV sector and help its transition to zero-emission vehicles. The HDV sector has been heavily reliant on diesel fuels for several reasons. Diesel fuel's high gravimetric and volumetric energy density (as a highly combustible liquid fuel) make it one of the optimal choices for an onboard energy source. Moreover, there have been decades of technological developments in vehicle design and well-established manufacturing processes surrounding the diesel ICE drivetrain. In addition, the petroleum processing infrastructure is fully mature, providing a stable diesel fuel supply at an economical price tag.

For zero-emission vehicles such as BEVs and FCEVs to be competitive with conventional diesel HDVs from the perspective of operations, a significant carbon emission tax or strong regulation restricting diesel vehicles must be put forth. Currently, as shown in Figure 3 and 4, both BEVs and FCEVs are not as competitive as diesel trucks to both fleet operators and shippers. In comparison, diesel trucks provide the largest cargo capacity over the zero-emission alternatives by a significant margin, allowing fleet operators to generate large amounts of revenue while keeping a low levelized cost of shipment to the shippers.

Using the weight-adjusted-distance pricing structure, we have found that in a free market scenario without regulation to reduce the use of carbon-emitting vehicles, a sufficient carbon tax that can triple the price of diesel from its existing value is necessary for H2 FCEV to be economically competitive, assuming a futuristic hydrogen price of 2 $USD/kgH2$. This represents a diesel price close to 6-12 USD/gal. Looking at the existing tax on carbon emissions implemented by state governments such as California, a carbon tax of 0.00452 USD/gal of diesel is too small to have a significant effect on the operational economics of diesel trucks [59].

4.4 Limitations and Assumptions

While the presented model provides a straightforward avenue to compare the trade-offs between zero-emission drivetrains and conventional diesel HDVs in terms of energy storage and operational techno-economics, several limitations exist.

First, the modeled results only capture the techno-economics of the cargo freight from an operational perspective, primarily focusing on the operational cost of energy and cargo freight revenue as they are directly associated with the energy storage and cargo capacity of vehicles designed for each drivetrain. Secondly, The model does not capture the capital costs of the vehicle and the drivetrain components as these numbers remain highly uncertain and likely to change depending on policies, technology maturity, and production volume. Moreover, labor costs and maintenance costs were not captured in this study. Currently, maintenance costs of Li-BEV and H2 FCEV remain unclear, since HDVs using these drivetrains are still in the early commercialization or prototype phase. While Efforts have been made to provide a simulated estimate of the maintenance costs for Li-BEVs and H2 FCEVs [60], these estimates remain speculative since zero-emission fleets have yet to enter wide-scale operation. Also, the maintenance effort will likely improve as the vehicle design matures and the workforce becomes more acquainted with these new zero-emission drivetrains. Furthermore, the labor costs of the driver(s) are likely insensitive to the drivetrain architecture, since the time it takes for a vehicle to travel an assigned distance likely stays the same. However, if the driver is on duty during the recharging period, the Li-BEVs may incur slightly higher labor costs compared to diesel or H2 FCEVs, due to the amount of downtime necessary for charging.

The drivetrain efficiency and its energy consumption are assumed to be fixed parameters, while their fuel economies may vary based on the cargo weight, road conditions, and traffic. Prior efforts were made to develop a model to better capture these road dynamics and their effect on the energy efficiency of the zero-emission drivetrain [40]. The dry weight of the unloaded vehicle without energy storage is assumed to be a fixed parameter for all drivetrains. In reality, the vehicle's dry weight may vary depending on the exact drivetrain design and the components used in the vehicle, which is challenging to fully characterize given the early technological readiness of some of these vehicle concepts. While the result provides an approximated volume footprint of a typical sleeper cab as a benchmark for comparison, the actual amount of space that can be used to house onboard energy storage will need further investigation. As these Li-BEV and H2 FCEV drivetrains mature in the coming years, future work can be done to better characterize the weight and volume allocations of these new zero-emission drivetrain architectures. In addition, the wt% of the energy storage systems are approximated values based on literature reviews and industry reports, which may differ from an actual vehicle depending on the design of the storage structure. For example, some vehicle manufacturers will add a protective metal frame surrounding the battery pack, which decreases the wt% of the overall battery storage system.

While this investigation uses Li-BEVs and H2 FCEVs as our primary focus for potential zero-emission options due to their technological promise toward wide-scale adoption, there are other decarbonization pathways currently explored by researchers and industry stakeholders as well, such as biofuels, liquid hydrogen storage, and onboard carbon capture systems. While these pathways are in different phases of technological readiness, they potentially can be additional options that aid carbon emission reduction. It is important to note that this study aims to provide key stakeholders (e.g. vehicle designers, fleet operators, and shippers) with explicit insights into the operational techno-economic implications of transitioning from diesel fleets to the most promising zero-emission options that exist currently. This study may answer key stakeholder questions such as "How does the cargo capacity of Li-BEV and H2 FCEV compare to conventional diesel trucks", or "For what ranges and applications does it make sense to transition to Li-BEVs versus H2 FCEVs?"

5. CONCLUSION

In seeking a viable path to fully decarbonize the existing diesel fleet in the HDV sector. there may not be one simple solution that will satisfy all range requirements, and a portfolio of zero-emission vehicles is likely needed. While the highly efficient Li-BEV HDVs show promise in the short- and medium-range for local freight deliveries, their application may be limited in the long-haul sector as any weight used for energy storage reduces the truck's freight capacity. The simulated results of the presented model elucidate the value propositions of Li-BEV drivetrains and H2 FCEV drivetrains to different stakeholders. We explore the impacts these drivetrain architectures have on operational techno-economics, primarily through onboard energy storage, from the perspective of fleet operators and shippers. It was found that Li-BEV HDVs are promising in the short- to medium-range (below 500 miles) and when cargo capacity is not a high priority. When considering decarbonizing long-haul freight-carrying HDVs above 750 miles, H2 FCEVs are likely a more promising drivetrain architecture than Li-BEVs from both technical and economic perspectives. Moreover, the results have shown that a significant carbon tax or regulations must be placed on diesel vehicles for zero-emission alternatives to be more techno-economically competitive. In addition, further development in refueling/recharging infrastructure is necessary, and advancements in onboard energy storage technologies should be made to ensure a successful transition to zero-emission vehicles in the HDV sector.

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