Life-Cycle Implications of Hydrogen Fuel Cell Electric Vehicle Technology for Medium- and Heavy-Duty Trucks

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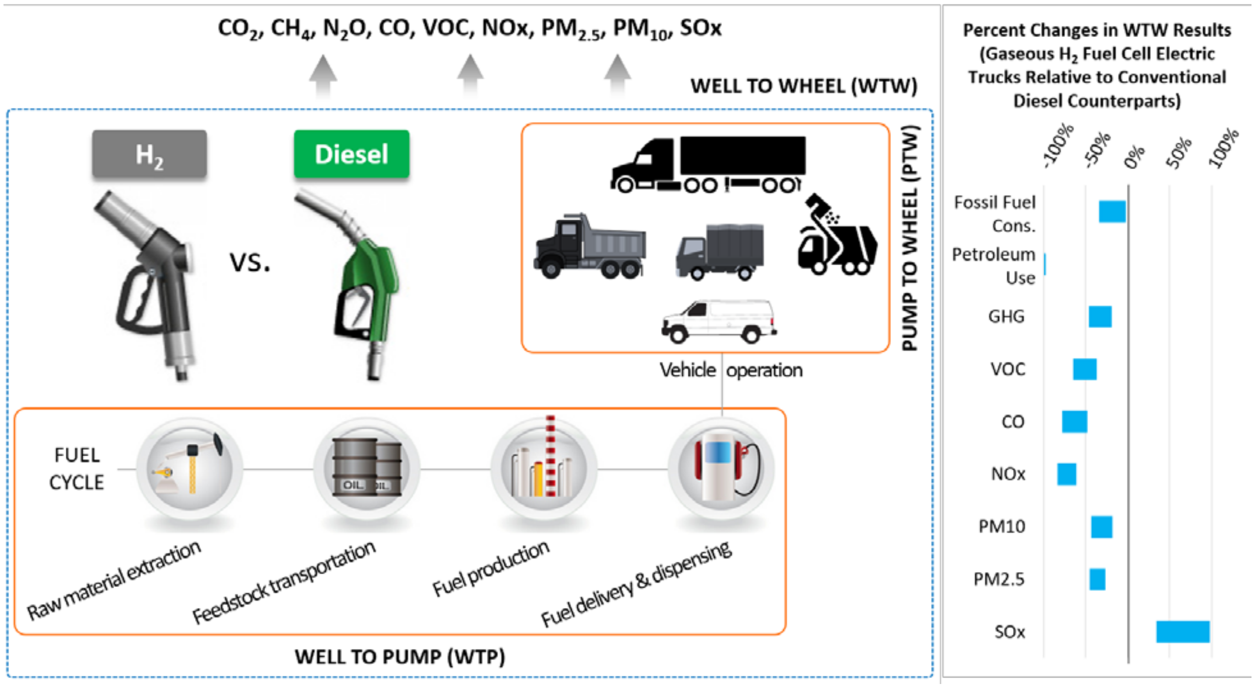
Abstract

This study provides a comprehensive and up-to-date life-cycle comparison of hydrogen fuel cell electric trucks (FCETs) and their conventional diesel counterparts in terms of energy use and air emissions, based on the ensemble of well-established methods, high-fidelity vehicle dynamic simulations, and real-world vehicle test data. For the centralized steam methane reforming (SMR) pathway, hydrogen FCETs reduce life-cycle or well-to-wheel (WTW) petroleum energy use by more than 98% compared to their diesel counterparts. The reduction in WTW air emissions for gaseous hydrogen FCETs ranges from 20-45% for greenhouse gases, 37-65% for VOC, 49-77% for CO, 62-83% for NOx, 19-43% for PM10, and 27-44% for PM2.5, depending on vehicle weight classes and truck types. With the current U.S. average electricity generation mix, FCETs tend to create more WTW SOx emissions than their diesel counterparts, mainly because of the upstream emissions related to electricity use for hydrogen compression/liquefaction. Compared to gaseous hydrogen, liquid hydrogen FCETs generally provide smaller WTW emissions reductions. For both the gaseous and the liquid hydrogen pathways for FCETs, because of electricity consumption for compression and liquefaction, spatio-temporal variations of electricity generation can affect the WTW results. The WTW emission reduction benefits of FCETs are estimated to be robust.

Graphical Abstract



Highlights

- H_2 fuel cell electric trucks provide life-cycle petroleum use and air emission reductions.
- Electricity consumption is influential for H_2 compression and liquefaction.
- Regional electricity energy sources affect the life-cycle emissions of fuel cell trucks.
- For urban and local operation, life-cycle benefits of fuel cell electric trucks are robust.
- Renewable hydrogen technology further decreases life-cycle energy use and emissions.

Keywords

Hydrogen fuel cell electric vehicle; zero emission vehicle; life-cycle analysis; fuel economy; air emissions; sustainable transportation

1. Medium- and Heavy-Duty Truck Electrification

Medium- and heavy-duty (MHD) vehicles account for a significant portion (20–25%) of energy consumption and air emissions in the U.S. transportation sector. MHD vehicles, around 11 million trucks and fewer than 1 million buses, represent only 4.5% of the 260 million vehicles on the road nationally [1]. Although they compose only a small share of the national vehicle population, MHD vehicles are the second-largest energy consumers and greenhouse gas (GHG) emitters, behind only light-duty vehicles that include passenger cars, sports-utility vehicles, and pickup trucks [1, 2, 3]. Furthermore, MHD vehicles' energy use is growing faster than any other on- or off-road vehicle segment or transportation mode. Although the transit bus market has reduced its petroleum consumption to just over half of the total fuel consumed by transit buses [4], the majority of MHD trucks still run on petroleum diesel fuel [5, 6, 7].

Diesel-powered MHD trucks have a tremendous impact on national and local air pollution. Nationally, MHD diesel trucks account for approximately 30% of total NOx, PM2.5, and PM10 emissions from mobile sources [6]. In terms of local air quality, the impact of MHD trucks can be even more significant. For example, on the southern coast of California where smog (ground-level ozone) is a serious public health concern, MHD diesel trucks contribute 33% of area-wide NOx (a precursor of smog formation) emissions from all stationary and mobile sources [8]. Further, low-income and/or minority communities can be more adversely affected than other population groups by the air pollutants from diesel trucks/buses [9]. Therefore, reducing energy consumption and air emissions of MHD diesel trucks is crucial to achieving sustainable transportation, protecting public health, and improving environmental justice at the local, regional, and national levels.

To improve MHD trucks' energy efficiency and reduce their air emissions, electric vehicle technologies (e.g., battery electric or hydrogen fuel cell electric) are emerging as viable options. In general, electric trucks have two major advantages over conventional diesel trucks. First, the energy efficiency of an electric powertrain is much higher than that of its diesel counterpart, mostly due to the large heat loss (about 60% of fuel input) of internal combustion engines [10, 11]. Second, electric trucks create no direct on-road emissions, other than those related to evaporation (e.g., paint) and wear (e.g., tires and brakes). It is true that today's diesel trucks create far less emissions than their predecessors, owing to the ever more stringent national standards for heavy-duty engine emissions and advances in diesel engine and after-treatment technology. That said, aside from powertrain electrification, there is a potential for further reduction of diesel trucks' tail-pipe emissions – for instance, by narrowing the gap between certified and real-world emissions, or by introducing next-generation standards [12]. Nonetheless, vehicle electrification, with the advantage of zero tail-pipe emissions, can provide a deep reduction in on-road air emissions from MHD trucks and significantly improve air quality.

2. Hydrogen Fuel Cell Electric Trucks (FCETs)

Battery electric and hydrogen fuel cell electric vehicles are the two leading MHD truck electrification technologies. Like battery electric trucks, hydrogen fuel cell electric trucks (FCETs) create zero tail-pipe emissions and are solely driven by electric motors. However, a FCET powertrain is typically less efficient than that of a battery electric truck, and hydrogen (around \$0.45/kWh, for early light-duty fuel cell vehicle markets) is currently more expensive than electricity (around \$0.1/kWh, national average without demand charges) [13]. Nevertheless, hydrogen cost is expected to decrease with economies of scale and improved utilization of hydrogen refueling stations. Moreover, compared to battery electric trucks, FCETs generally have a longer driving range and refuel much more rapidly (only several minutes to fill up empty tanks, similar to the 10–12 minutes for conventional diesel).

MHD hydrogen FCETs can largely be categorized by vehicle energy system configuration (fuel cell– or battery–dominant) and vehicle weight classifications. Battery-dominant FCETs rely on a relatively large-capacity battery charged with electricity drawn from the power grid, for which onboard hydrogen energy system serves as a range extender. In contrast, fuel cell–dominant FCETs carry a smaller battery and are primarily powered by electricity from the hydrogen fuel cells. However, the distinction between battery–dominant and fuel cell–dominant FCETs is not always clear. Regardless of fuel (e.g., diesel or hydrogen) or propulsion technologies (e.g., fuel cell– or battery–dominant), on-road MHD vehicles are subdivided into eight different gross vehicle weight rating (GVWR) classes, spanning Classes 2b through 8b [14]. GVWR is a measure of load-carrying capability, which includes the weight of the vehicle itself (or curb weight) and the maximum payload the vehicle can carry. Class 2b includes vehicles with a GVWR between 8,501 and 10,000 lbs, mostly larger pickup trucks and vans. Class 8b vehicles with a GVWR above 60,000 lbs are predominantly combination tractor-trailers ("18-wheelers"), which are the heaviest vehicles on the road.

Most of the hydrogen FCETs on the road today, with driving ranges of 150–200 miles for urban, local, and short-haul operation, are based on gaseous hydrogen compressed at 350 bar for onboard energy storage (mostly Type III tanks with metal liner and composite overwrap). The same onboard hydrogen storage pressure (350 bar) may also be adopted for FCETs that are used for regional or long-haul operation [15], although it would require more space for larger onboard storage capacity. The onboard hydrogen compression pressure (350 bar) for FCETs is lower than 700 bar for light-duty vehicles (mostly Type IV tanks with polymer liner and composite overwrap) with over 300 miles of driving range. The lower onboard hydrogen compression pressure (350 bar) and metal liner tanks for FCETs eliminate the pre-cooling requirement for fast re-fueling [16].

In the United States, nearly half of MHD trucks are used for urban, local, and short-haul operation, with a daily travel distance less than 200 miles [6]. Switching all those diesel trucks to FCETs (hypothetically) is equivalent to eliminating approximately 30% of all on-road NOx emissions from the entire MHD truck sector [17]. Although FCETs can remove tail-pipe or on-road direct emissions as such, the point or origin of emissions and corresponding environmental burden may shift from tail-pipe or the road network to upstream fuel production plants. Therefore, when comparing conventional diesel and fuel cell electric trucks, it is important to incorporate the indirect (upstream) emissions from fuel production beyond vehicle operation. To this end, life-cycle analysis (LCA) is a useful framework that incorporates and compares all direct and indirect environmental impacts over the entire well-to-wheel (WTW) chain.

When it comes to LCA of medium- and heavy-duty hydrogen FCETs, despite the growing interest in FCET technology, life-cycle energy use and emissions estimates for FCETs are scarce. Even the National Petroleum Council (NPC) report [18], one of the most comprehensive analyses of transportation fuel and vehicle technologies in recent years, lacks information about the life-cycle energy efficiency and environmental impacts of hydrogen FCETs. Some piecewise WTW analyses [9, 19] exist, but those studies focus on urban transit buses. There is a relatively large number of life-cycle studies for battery electric medium- and heavy-duty trucks [20, 21, 22], which touch on an array of life cycle metrics: energy efficiency, water consumption, air emissions, and cost. However, comparable life-cycle studies are virtually nonexistent for hydrogen FCETs. To fill this knowledge gap, there is a research need to quantify and evaluate life-cycle energy and the environmental benefits and trade-offs for FCETs in comparison with other fuel-vehicle technologies, particularly in the United States. This study is a first-of-its-kind attempt to develop representative and reliable estimates of life-cycle fuel consumption and air emissions for a comprehensive set of FCETs based on a coherent set of assumptions, methods, and models. This study focuses on the life cycle of the fuel (also as known as a WTW analysis). The impact of vehicle manufacturing or end-of-life, and infrastructure construction, maintenance, operation, or end-of-life are outside of scope for this analysis and are left for future work.

The main objective of this study is to compare a variety of hydrogen FCETs (Classes 2b through 8b) and conventional diesel counterparts in terms of WTW energy use and air emissions (GHGs and criteria air pollutant [CAP] emissions). In doing so, this study proposes adjustments to the well-established U.S. Environmental Protection Agency (EPA) and National Highway Traffic Safety Administration (NHTSA) method of calculating fuel consumption for MHD vehicles [14]. The proposed adjustments allow the EPA/NHTSA method to be applied for not only conventional diesel but also electric vehicles, including FCETs. This methodological adjustment also enables regional analysis and spatio-temporal aggregation to develop representative national average values. Most importantly, the analysis is built upon a high-fidelity vehicle dynamic simulation models and real-world vehicle test data, which significantly improves the credibility and quality of the presented results. In addition to the development of baseline WTW results for conventional diesel trucks and FCETs, this study also sheds light on the robustness of FCETs' life-cycle environmental benefits in the context of potential advances in vehicle and fuel production technologies, including diesel engine efficiency improvements and advanced hydrogen fuel production pathways for FCETs via water electrolysis through integration with wind or solar power generation.

All in all, the contribution of this study is fourfold. First, this study develops life-cycle energy use and air emissions estimates for a comprehensive set of medium- and heavy-duty hydrogen FCETs, which are lacking in the current body of literature. Second, this study proposes a methodological adjustment for the MHDV fuel economy and GHG emissions standards so as to be applicable for a regional life-cycle analysis as well as (fuel cell or battery) electric truck technology. Third, this study integrates high-fidelity vehicle dynamic simulation and real-world vehicle test data to evaluate life-cycle benefits and trade-offs of MHD FCETs. Fourth, this study not only compares conventional diesel and hydrogen FCET technology but also incorporates potential technological advances related to conventional diesel trucks, which helps reveal the robustness of the benefits (if any) of emerging hydrogen FCET technology.

3. Method

WTW energy consumption and emissions consist of upstream fuel production and delivery (well-to-pump, WTP), and vehicle operation (pump-to-wheel, PTW). Because FCETs create zero tail-pipe emissions from vehicle operation, most of the discussions in this section focus on estimating PTW fuel consumption (not emissions) of FCETs compared to conventional diesel. The third and last part touches on PTW emissions (mainly for conventional diesel), as well as integration with upstream WTP components (fuel production and delivery) for a comparative WTW analysis of conventional diesel trucks and FCETs.

3.1. Vehicle Component Sizing and Dynamic Simulation

Although several hydrogen FCET developers (e.g., Kenworth, TransPower, Toyota) exist in the United States, FCETs are generally in their infancy (mostly custom-built prototypes), and thus only limited real-world vehicles and data are available. Given the early stage of FCET technology and market development, high-fidelity vehicle dynamic simulation provides a good alternative for evaluating fuel efficiency. For vehicle dynamic simulation, this study employs the Autonomie model, one of the most advanced and well-verified vehicle dynamic simulators.

Because vehicular energy consumption can be significantly affected by vehicle design attributes and performance metrics (e.g., vehicle test weight, frontal area, maximum acceleration, rated power), it is critical to control those parameters so that conventional diesel trucks and hydrogen FCETs are tested and compared on an apples-to-apples basis. The vehicle components are sized based on truck market information as well as in-use truck activity data, including Fleet DNA [23] and VIUS [24]. The method and data sources for component sizing are described in detail by Vijayagopal [25] and Kast et al. [26]. For each of the vehicle segments or GVWR classes, the modeled vehicles in Autonomie, listed in Table 1, have statistically representative attributes and performances of the corresponding trucks on the road.

Hydrogen FCETs are inherently based on a series hybrid-electric vehicle system, propelled solely by electric motors and drawing energy from a high-voltage battery and fuel cell system. To avoid potential bias related to the MHD hybrid-electric vehicles [27], battery state of charge (SOC) is kept the same at the beginning and end of the test cycle(s), ensuring zero net energy change for a traction battery. FCETs tested in this study are fuel cell–dominant, powered by electricity from the fuel cell system most of the time, and only partly supported by the traction battery when necessary (e.g., acceleration).

Once the vehicle component sizing and design are complete, both conventional diesel trucks and FCETs are simulated over multiple test cycles. Spatial and temporal aggregation are also conducted on these vehicle dynamic simulation results to develop representative national average values as described in Section 3.2. The overall process is depicted in Figure 1.

3.2. Adjusted EPA/NHTSA Method for Fuel Consumption

The most recent (phase 2) EPA/NHTSA fuel efficiency and GHG emissions standards for MHD vehicles [14] are based on a weighted average of three driving cycles (Figure 1), to which fuel consumption and

Table 1. List of MHD trucks evaluated, basic parameters, idle fuel rate, and fuel economy ratio

<table>
<tr><th rowspan="2">Test Vehicle</th><th rowspan="2">GVWR Class</th><th colspan="2">Curb Weight (tonnes)</th><th rowspan="2">Payload (tonnes)</th><th rowspan="2">Idle Fuel Rate for Diesel Trucks[a] (gal/hour)</th><th rowspan="2">Weighting Strategy for Composite Values[b]</th><th rowspan="2">Fuel Economy Ratio[c] (fuel economy, MPDGE, for conventional diesel trucks)</th></tr>
<tr><th>D</th><th>FC</th></tr>
<tr><td>Pickup Truck and Van</td><td>2b</td><td>2.95</td><td>2.81</td><td>1.1</td><td>0.36 ± 0.08</td><td>MP</td><td>1.6
(20.8)</td></tr>
<tr><td>Straight Truck or Walk-in Van</td><td>4</td><td>4.41</td><td>4.46</td><td>2.4</td><td>0.73 ± 0.12</td><td>U</td><td>2.1
(10.1)</td></tr>
<tr><td>Medium Heavy-duty Vocational Truck</td><td>6</td><td>3.87</td><td>3.75</td><td>4.8</td><td>0.73 ± 0.2</td><td>U</td><td>2
(8.3)</td></tr>
<tr><td>Refuse Truck</td><td>8a</td><td>8.01</td><td>8.14</td><td>9.8</td><td>0.81 ± 0.2</td><td>U</td><td>1.81
(5.7)</td></tr>
<tr><td>Construction Truck</td><td>8b</td><td>7.52</td><td>7.91</td><td>22.6</td><td>0.75 ± 0.1</td><td>U</td><td>1.72
(7.4)</td></tr>
<tr><td>Tractor-trailer</td><td rowspan="2">8b</td><td rowspan="2">10.67</td><td rowspan="2">10.21</td><td rowspan="2">20.5</td><td rowspan="2">0.63 ± 0.16</td><td>DC</td><td>1.45
(7.4)</td></tr>
<tr><td>Drayage Truck[d]</td><td>U</td><td>1.8
(6)</td></tr>
</table>

[a] Median values with standard deviation.

[b] Defined in the EPA and NHTSA standards [14]: Urban (U), Multi-purpose (MP), Day Cabs (DC), etc.

[c] FCETs relative to conventional diesel trucks, using spatially and temporally aggregated national average values. For EPA/NHTSA test cycle-specific fuel economy values, see Lee et al. [28]. Fuel consumption is the inverse of fuel economy ratio. Because of the same payload test condition, fuel consumption and load-specific fuel consumption (LSFC) ratios are the same.

[d] Drayage truck is based on tractor-trailer (or short-haul combination truck). Typical operating condition of drayage trucks is mostly urban or local, whereas typical (day cab) tractor-trailers have almost a 50/50 share of urban and highway driving.

emissions related to idling activities are further added after weighting. The EPA/NHTSA method provides a coherent and well-established methodological platform that is applicable across different GVWR classes and vocations. However, the EPA/NHTSA method does not explicitly consider electric vehicles (e.g., FCETs). More importantly, the EPA/NHTSA method does not account for location-specific fuel consumption or emissions, which makes it difficult to apply in a regional analysis. To overcome those

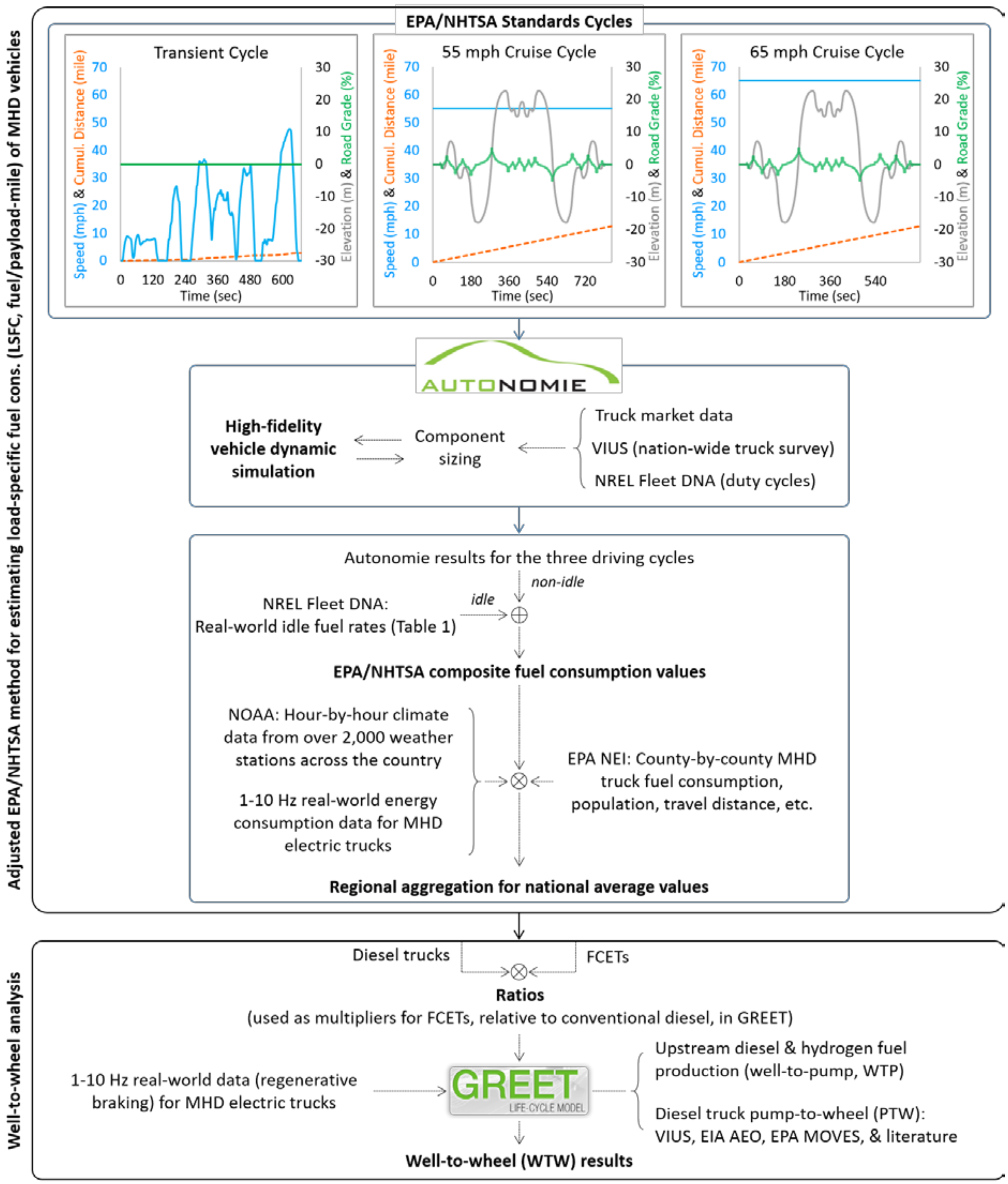


Figure 1. Methods, input data, and models for well-to-wheel (WTW) analysis.

limitations, this study uses the following adjusted EPA/NHTSA formulas. This is universally applied (with different input parameter values) for all the classes and types of trucks considered (see Table 1):

$$FC_{composite} = FC_{NI} + \frac{1}{\alpha_I \bar{V}_{moving}} FR_I \tag{1}$$

$$FC_{NI} = w_{NI,Transient}\left(\frac{G_{Transient}C_{climate} + \bar{P}_{ESS,Out,HVAC}T_{Transient}}{D_{Transient}}\right) + w_{NI,55mph}\left(\frac{G_{55mph}C_{climate} + \bar{P}_{ESS,Out,HVAC}T_{55mph}}{D_{55mph}}\right) + w_{NI,65mph}\left(\frac{G_{65mph}C_{climate} + \bar{P}_{ESS,Out,HVAC}T_{65mph}}{D_{65mph}}\right) \quad (2)$$

$$FR_I = w_{I,drive}\left(\overline{FR}_{I,drive} + \bar{P}_{ESS,Out,HVAC}\right) + w_{I,parked}\left(\overline{FR}_{I,parked} + \bar{P}_{ESS,Out,HVAC}\right) \quad (3)$$

$$\bar{P}_{ESS,Out,HVAC} = \frac{\bar{P}_{HVAC}}{\bar{\eta}_{FuelCell}} \quad (4)$$

where $FC_{composite}$ is the EPA/NHTSA composite value of fuel consumption (i.e., fuel use per payload-mile) based on both non-idle and idle modes of vehicle operation; FC_{NI} is non-idle fuel consumption (fuel/distance), which is a weighted sum of the individual results for three test cycles; FR_I is idling fuel rate (fuel/hour), which is converted to fuel consumption with the idle weighting factor (α_I) and moving average speed ($\bar{V}_{moving}$ in miles/hour); G is the fuel consumption result from Autonomie for each driving cycle; $C_{climate}$ is correction (or penalty) factors for climate-dependent powertrain efficiency, which may vary with vehicle technology, duty cycle, temperature, and so on; D and T are total distance traveled and time spent for completing each test cycle, respectively; $\bar{P}_{ESS,Out,HVAC}$ is the output power (in kW) drawn from the energy storage system (ESS) (e.g., fuel tank) to meet onboard heating, ventilating, and air conditioning (HVAC) demand ($\bar{P}_{HVAC}$); $\bar{\eta}_{FuelCell}$ is average fuel cell efficiency for delivering $\bar{P}_{HVAC}$, which is assumed to be 50% based on Autonomie simulations; and all the other parameters (α and w) are unitless weighting factors defined in the EPA and NHTSA standards [14].

Unless otherwise noted, fuel consumption is in lower heating value–based diesel gallon equivalents (DGE) for both conventional diesel trucks and FCETs, fuel rate is in DGE/hour, HVAC power is in kW, payload is in metric tonnes (tonnes), and distance is in miles. As defined in the EPA and NHTSA standards [14], Eq. (2) is for distance-weighted calculations, and Eq. (3) is for time-weighted calculations. These are combined as in Eq. (1). For convenience, Eqs. (2) and (3) do not show the unit conversion between DGE/hour and kW. Fuel consumption in Eq. (1) can be converted to load-specific fuel consumption ($LSFC_{composite}$) or fuel economy ($FE_{composite}$) as follows:

$$LSFC_{composite} = \frac{FC_{composite}}{payload} \quad (5)$$

$$FE_{composite} = \frac{1}{FC_{composite}} \quad (6)$$

LSFC (load-specific fuel consumption) is an important metric in the MHD vehicle sector, because it accounts for the different load-hauling capabilities of different vehicle technologies or weight classes. However, we also use fuel consumption (DGE/miles) and fuel economy (miles/DGE, MPDGE) without payload factor throughout the paper for two reasons. First, fuel consumption or fuel economy is more physically intuitive and easier to understand than LSFC. Second, we use the same payload condition for both diesel and fuel cell trucks within each GVWR class and vehicle type evaluated in this study (Table 1). Therefore, whether the results are load-specific or not, there is no difference in overall comparison between FCETs and diesel counterparts. Nonetheless, if necessary, one can simply divide fuel consumption (DGE/mile) or emissions (grams/mile) by the payload factor in Table 1 to obtain load-specific fuel consumption (DGE/tonne-mile) or emissions (grams/tonne-mile).

Input values and the underlying logic of the unitless weighting factors (α_I, w_{NI}, and w_I), as well as other basic parameters ($\bar{V}_{moving}$) in Eqs. (1)–(4), are all specified in the EPA and NHTSA standards [14]. Test cycle-specific fuel consumption (G) values are from the Autonomie simulations, the results of which are very similar to the surveyed in-use data [28]. Climate-related powertrain efficiency penalty factors ($C_{climate}$) are assumed to be 1, and more detailed investigations are left for future work.

Real-world idle fuel rates from Fleet DNA [23, 29], presented in Table 1, are used for $\overline{FR}_I$ in Eq. (3). For simplicity, idling fuel consumption is assumed to be the same for both driving and parked conditions. As illustrated by Lee et al. [28], Fleet DNA has a significantly larger sample size and provides more transparent, detailed, and reliable idle fuel rate data than other alternative data sources such as EPA MOVES [30]. Using more accurate and reliable idle fuel rates is important, particularly because additional idle fuel consumption specified in the EPA/NHTSA standards can be significant in terms of overall fuel consumption, as illustrated in Figure 2a.

It is well known that the fuel efficiency of electric vehicles (including FCETs) can be more sensitive to local climate conditions (e.g., hot and cold) in comparison with internal combustion engine vehicles. To account for such climate-related impacts and technology-dependent variations, we conduct geographical (county-by-county) and temporal (hour-by-hour) aggregation, based on hourly climate data collected across the country [31]. Corresponding to hourly climate profiles, we estimate HVAC power demand using proprietary real-world data for diesel and battery electric trucks gathered from industry partners and collaborators [28].

For representative national average fuel consumption values, location- and time-specific results are

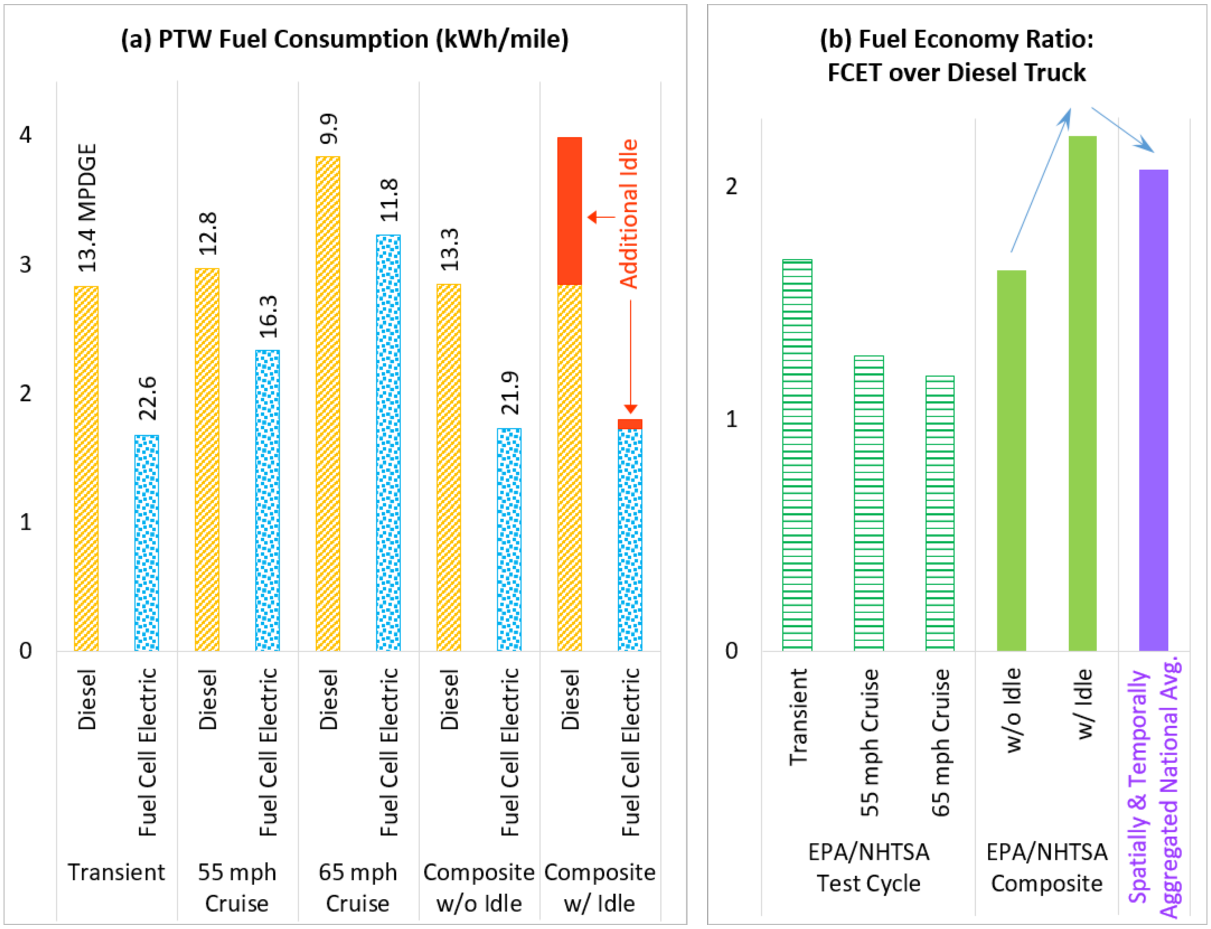


Figure 2. (a) Evolution of fuel consumption and (b) fuel economy ratio for an example GVWR Class 4 straight truck, as a result of weighted average with additional idle for EPA/NHTSA composite values and spatiotemporal aggregation for representative national average. Fuel economy of the corresponding baseline diesel truck in GREET is 10 MPDGE. Combined with the national average fuel economy ratio above, the representative fuel economy of a GVWR Class 4 FCET is estimated to be 21 MPDGE.

aggregated for a full year and weighted spatially based on county-by-county fuel consumption (used as a proxy for spatial distribution of vehicle activity) for each GVWR class and truck type [6]. Spatial distributions of vehicle population and travel distance were also tested to develop the spatial weighting for national averages, but the results were not very different from the one based on fuel consumption.

Figure 2b shows how the fuel economy ratios for FCETs over conventional diesel change from test cycle-specific Autonomie simulation results to final (adjusted composite EPA/NHTSA) values as idle fuel consumption and spatio-temporal aggregation are incorporated. Inclusion of additional idle fuel consumption increases the fuel economy ratio, because it decreases fuel economy of diesel trucks more than it does for FCETs. Spatio-temporal aggregation has the opposite effect, decreasing the fuel economy ratio, predominantly because HVAC power demand tends to degrade FCET fuel economy more than it does for diesel trucks. It is worth mentioning that overall impacts related to HVAC or spatio-temporal aggregation may not be very significant, because seasonal fluctuations or spatial extremes cancel out over the course of a year and across different locations. On average, as Table 1 indicates, FCETs achieve around 80% better (PTW) fuel economy over conventional diesel counterparts for the same payload conditions.

3.3. Well-to-Wheel (WTW) Analysis

For WTP fuel consumption and emissions associated with upstream fuel production and delivery, Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) [32] is used. GREET was recently updated with new emissions factors for petroleum diesel fuel production from refineries, as well as hydrogen production from natural gas steam methane reforming (SMR) plants, based on a significantly larger sample and the most up-to-date emissions data [33, 34]. FCETs can be powered by either gaseous hydrogen (G.H2, compressed at 350 bar without pre-cooling, as mentioned previously) or liquid hydrogen (L.H2) fuel, and this study considers both fuel types. For hydrogen (G.H2 or L.H2) FCETs, electricity consumption for hydrogen refueling (e.g., compression) can have a significant impact on overall (WTP and WTW) energy consumption and emissions. Electricity production is region-specific depending on generation fuel mix and technology. Therefore, in addition to national averages, regional electricity and corresponding emissions factors (based on GREET) are incorporated into the analysis.

As of 2017, U.S. average WTP efficiency of conventional diesel is around 83%, whereas it is about 57% for G.H2 and 42% for L.H2. Given the lower upstream (WTP) efficiency of hydrogen fuel (G.H2 and L.H2), any life-cycle efficiency advantage of hydrogen FCETs mainly depends on the PTW (vehicle operation) efficiency differential between FCETs and diesel counterparts; FCETs achieve 50–100% better PTW efficiency compared to their diesel counterparts (Table 1).

For PTW fuel consumption and emissions of conventional diesel trucks, existing national average values in GREET are used for model year 2016 trucks. The PTW fuel consumption and emissions factors for conventional diesel trucks are based on a nationwide truck survey [24], the Energy Information Administration's Annual Energy Outlook (EIA AEO) fuel economy projections [35], and EPA MOVES [29]. For FCET PTW fuel consumption, the ratios (national averages) developed above to compare fuel economy (or consumption) between FCETs and conventional diesel trucks are multiplied with the corresponding values for conventional diesel in GREET (Table 1 and Figure 1). Using these ratios rather than absolute values preserves the model consistency and existing structure of GREET. The models used in this analysis produced fuel economy results (absolute values) for diesel trucks that were very similar to the results from an in-use vehicle survey adopted in GREET [28].

Although FCETs have zero tail-pipe emissions, they still create on-road particulate matter emissions from tire and brake wear. It is assumed that FCETs create the same amount of tire wear emissions as diesel trucks do. For break wear emissions, however, the regenerative braking of electric trucks reduces the burden on conventional friction braking, resulting in a decrease of particulate matter emissions associated with brake wear. Accordingly, brake wear emissions of conventional diesel trucks are adjusted using the energy share (32–55%) of an electric drivetrain's regenerative braking in overall braking effort, based on the aforementioned proprietary electric truck test data.

4. Results and Discussion

4.1. Energy Consumption

In terms of life-cycle fossil fuel consumption, an FCET can almost eliminate petroleum use in comparison with a conventional diesel truck (Figure 3a). The baseline hydrogen fuel considered in this study is sourced from natural gas SMR, so the dominant fossil fuel source shifts from petroleum for conventional diesel trucks to natural gas for hydrogen FCETs. Overall fossil fuel consumption reduction varies by vehicle type and vocation, as well as hydrogen fuel type (gaseous or liquid). For example, GVWR Class 8b fuel cell electric drayage trucks powered by gaseous hydrogen (G.H2) use 22% less WTW fossil fuel compared to their conventional diesel counterparts. However, although they have the same vehicle structure and platform (Table 1), the reduction of fossil fuel use for typical day cab tractor-trailers is relatively smaller (3%). This difference is mainly attributable to different operating conditions. Typical combination short-haul trucks (or day cabs) split their time almost 50/50 between urban and highway driving. In contrast, drayage trucks usually operate more in urban and local driving conditions, where the efficiency gain of FCET over conventional diesel is higher. This also applies to Class 2b pickup trucks and vans that have a relatively larger share of highway driving than the other types of trucks (e.g., refuse trucks), which means that their reduction in fossil fuel use is also smaller (12%). Other than those two vehicle types (Class 2b pickup trucks/vans ad Class 8b tractor-trailers), overall WTW fossil fuel consumption reduction ranges from 18% to 34%. Largely because of the significant amount of electricity consumed for liquefaction, liquid hydrogen (L.H2) FCETs generally consume slightly more fossil fuel than conventional diesel trucks.

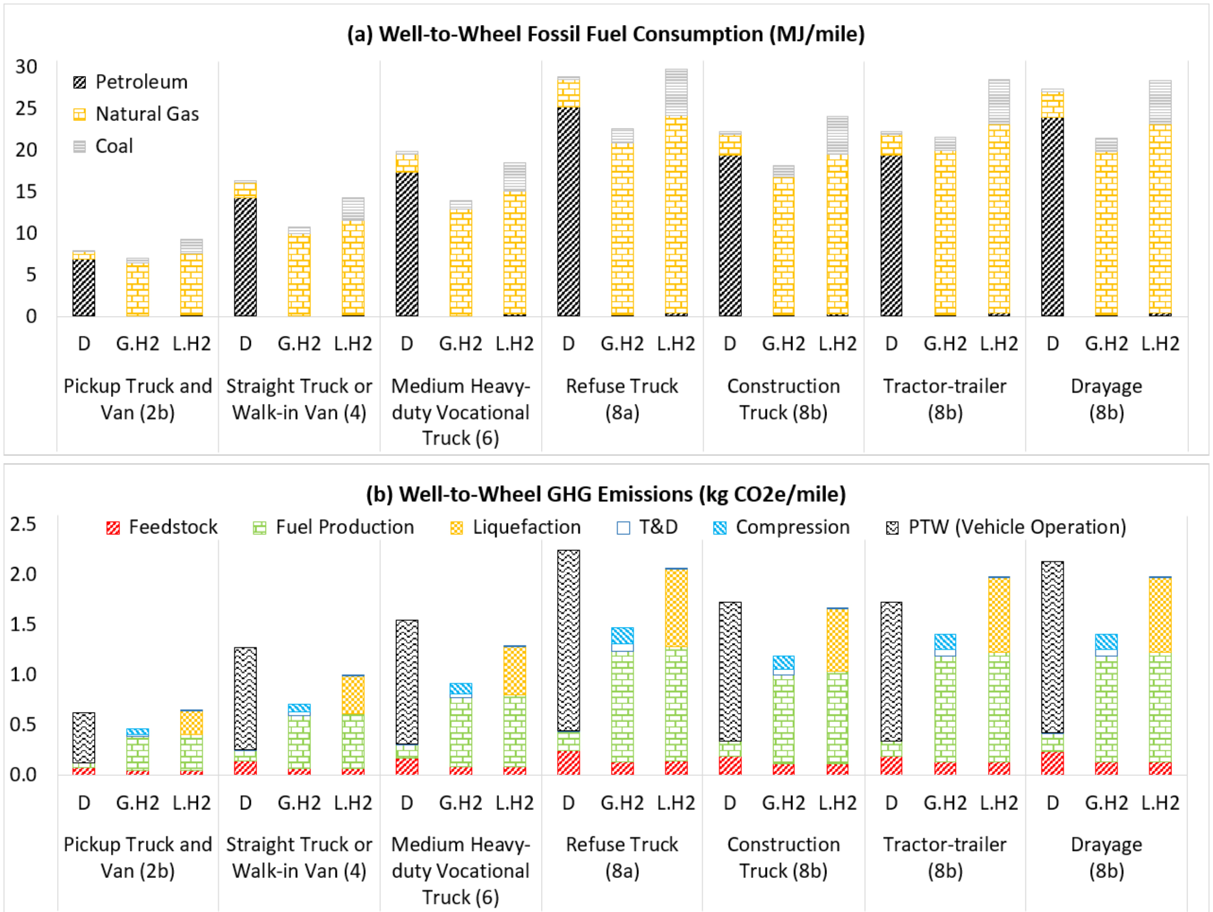


Figure 3. Life-cycle (WTW) fossil energy consumption (petroleum, natural gas, and coal) and GHG emissions by component (feedstock, fuel production, liquefaction, transmission and distribution [T&D], compression at hydrogen refueling stations, and vehicle operation [PTW]) for conventional diesel (D, ultra-low sulfur diesel), gaseous hydrogen (G.H2), and liquid hydrogen (L.H2).

4.2. Greenhouse Gas Emissions

Figure 3b illustrates that conventional diesel trucks and FCETs have very different structures of life-cycle GHG emissions. Tail-pipe exhaust GHG emissions account for the largest portion for conventional diesel trucks, but fuel production (natural gas SMR) is the dominant GHG emission source for hydrogen FCETs. For L.H2 FCETs, liquefaction is the second largest contributor to life-cycle GHG emissions. G.H2 FCET technology reduces GHG emissions by 19–45%, and the benefits of (G.H2) FCET technology are robust for all MHD trucks considered in this study. For L.H2 FCETs relative to conventional diesel, GHG emissions can be reduced by 22% for Class 4 straight trucks; however, emissions increase by 14% for Class 8b tractor-trailers, in part due to the burden of liquefaction, assuming the electricity for liquefaction is sourced from the U.S. average power generation mix.

4.3. Criteria Air Pollutants Emissions

Figure 4 shows WTW CAP (criteria air pollutant) emissions results for all the vehicles listed in Table 1, except drayage trucks. Due to the lack of tail-pipe emissions data for diesel-powered drayage trucks, only energy consumption and GHG emissions results are presented (in Figure 3) for drayage trucks. Figure 4 indicates that FCETs (particularly G.H2-powered) generally create much less life-cycle CAP emission in comparison with their conventional diesel counterparts. The CAP emission reduction potential may vary with GVWR class and vocation. The life-cycle CAP emissions reductions of G.H2-powered FCETs (relative to conventional diesel) are 37–65% for VOCs, 49–77% for CO, 62–83% for NOx, 19–43% for PM10, and 27–44% for PM2.5.

As Figures 3b and 5 imply, most of the air emissions reductions (GHG, VOC, CO, and NOx) can be attributed to the elimination of tail-pipe emissions. The significant reductions in VOC, CO, and NOx

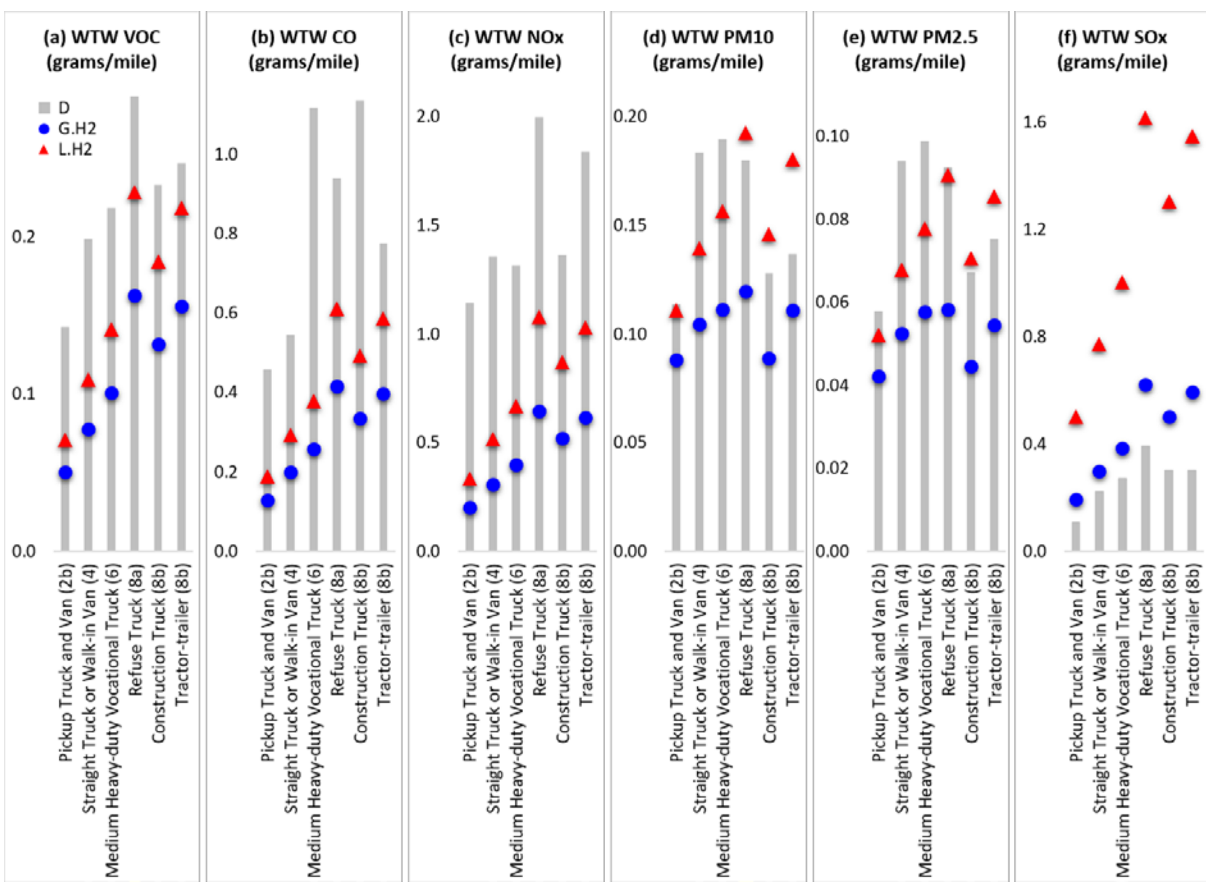


Figure 4. Life-cycle (WTW, well-to-wheel) criteria air pollutant (CAP) emissions for conventional diesel (D) and hydrogen FCETs powered by gaseous (G.H2) and liquid (L.H2) hydrogen. For load-specific CAP emissions (grams/tonne-mile), one can simply divide the per-distance values (grams/mile) by the payload listed in Table 1.

emissions for FCETs relative to conventional diesel have an important implication for areas (e.g., Los Angeles) where smog (ground-level ozone) is a serious concern. In other words, less-polluting FCETs, as an alternative to diesel trucks, could help reduce the risk of smog formation in those areas.

However, tail-pipe exhaust particulate matter (PM2.5 and PM10) emissions for diesel trucks account for a relatively smaller portion of overall life-cycle emissions (Figure 5). Along with upstream fuel production, tire and brake wear is the largest component of particulate matter emissions through the WTW chain. That being said, the benefits of FCETs' regenerative braking (reducing brake-wear particulate matter emissions) can be significant. For example, FCETs reduce 71% of on-road PM2.5 emissions of GVWR Class 8a refuse trucks compared to their conventional diesel counterparts; 70% of

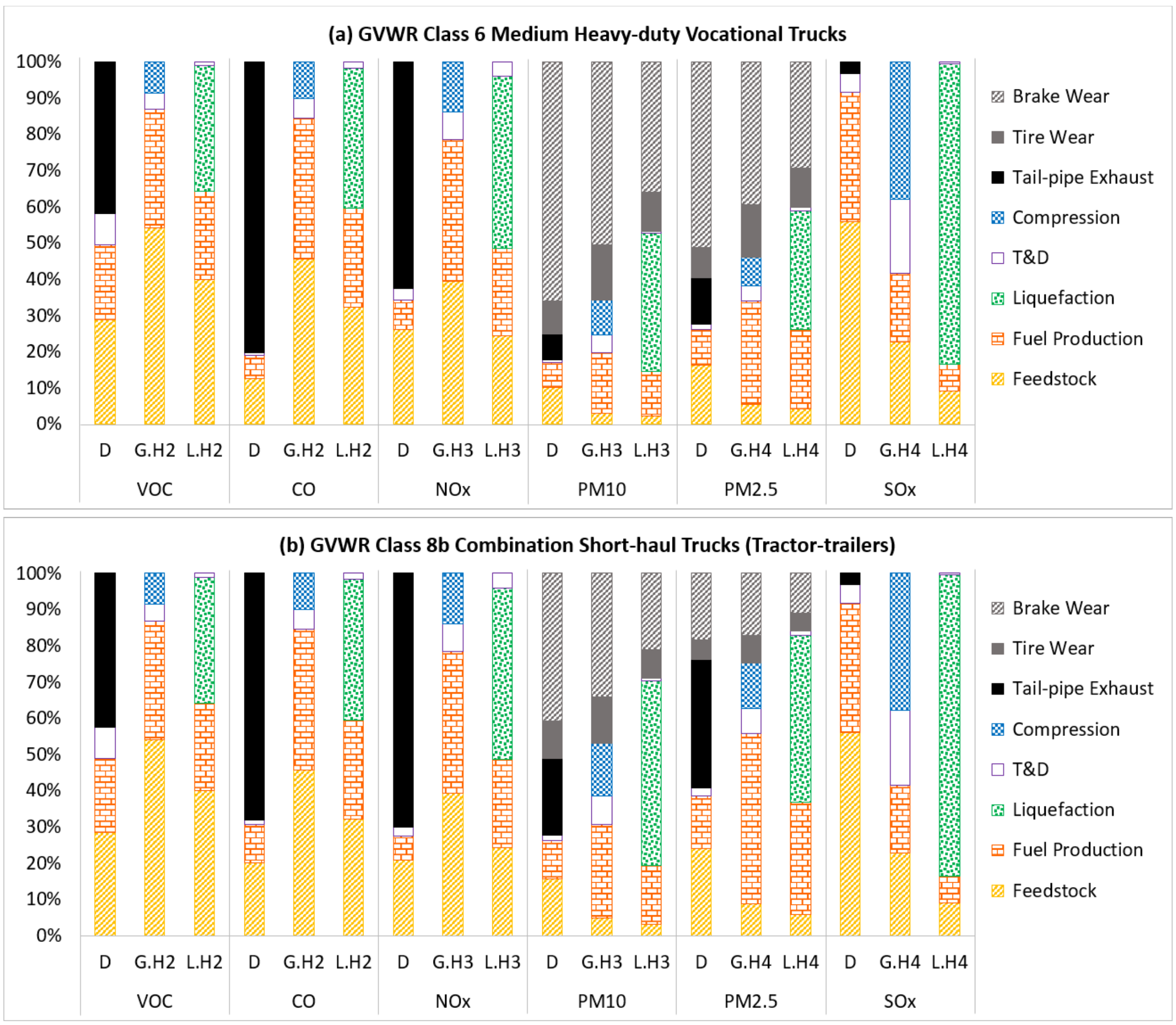


Figure 5. Criteria air pollutants (CAP) emissions by individual component through the WTW chain for (a) GVWR Class 6 medium heavy-duty trucks and (b) Class 8b combination short-haul trucks. Only percentage shares are shown; see Figure 4 for absolute values.

this reduction is due to the elimination of tail-pipe exhaust emissions and 30% is due to the reduction of brake-wear emissions by regenerative braking. Overall on-road PM2.5 emissions benefits of FCETs range from 39% to 73%. For typical combination short-haul trucks (tractor-trailers) that have relatively smaller portions of urban/local driving, the contribution of regenerative braking for on-road PM2.5 emissions reductions is smaller (14%). The difference between Figures 5a and 5b in terms of particulate matter emissions also illustrates the impact of aforementioned operating conditions (e.g., a relatively larger share of highway driving for typical day cab tractor-trailers). Overall, WTW PM2.5 and PM10 emissions of FCETs are lower (by 19–44%) compared to conventional diesel trucks.

As Figure 5 implies, sulfur oxide (SOx) emissions are higher for FCETs, mostly due to the emissions associated with electricity required for hydrogen compression or liquefaction. Liquid hydrogen FCETs create significantly higher WTW CAP emissions than gaseous hydrogen trucks, due to electricity consumed for liquefaction. Nonetheless, VOC, CO, and NOx emissions of liquid hydrogen FCETs are still lower than those of conventional diesel trucks, regardless of GVWR class or vocation. Liquid hydrogen FCETs lead to higher WTW SOx emissions than conventional diesel, and so do gaseous hydrogen FCETs.

4.4. Impact of Regional Electric Grid

As discussed earlier, FCETs consume a significant amount of electricity for hydrogen compression for G.H2 and hydrogen liquefaction for L.H2. Therefore, the regional electric grid and its future evolution are important factors in the life-cycle emissions of FCETs. Figure 6 shows how the life-cycle emissions comparison between FCETs and conventional diesel trucks can change with different regional electric grids and their electricity generation sources at present (2016) and in the future (2035). In Figure 6, except regional emissions factors for electricity generation, we used national average fuel economy values for simplicity, which produced constant lines for conventional diesel trucks across the regions. Baseline fuel economy values for model year 2016 were used to avoid any confounding effect of fuel economy improvement over time. In other words, the results and the changes between 2016 and 2035 shown in Figure 6 are related solely to the change in WTP upstream fuel (petroleum, electricity, hydrogen, etc.) production and delivery.

Note that the aforementioned benefits of GHG and CAP emissions reductions for FCETs are robust under various current and future regional electric grid conditions. Between 2016 and 2035, upstream (WTP) emissions for diesel fuel production and delivery decrease, but the reduction is generally not sufficient to negate the emissions reductions of FCETs over conventional diesel. The emissions reduction for

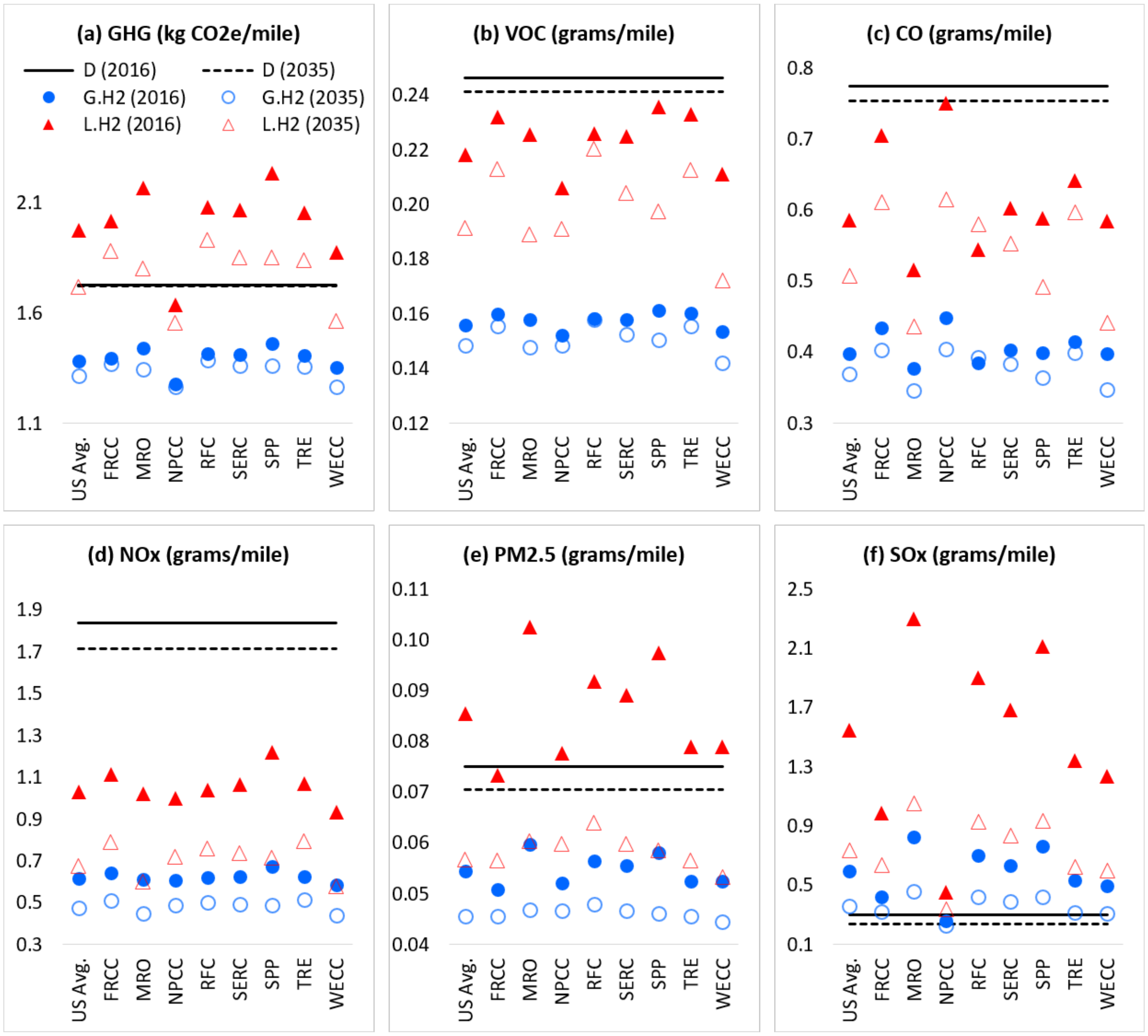


Figure 6. Impact of regional electric grid on WTW GHG and CAP emissions of an FCET (e.g., GVWR Class 8b combination short-haul trucks) in comparison with a conventional diesel truck, at present (2016) and in the future (2035).

Regional electric grids: Western Electricity Coordinating Council (WECC), Midwest Reliability Organization (MRO), Southwest Power Pool, RE (SPP), Texas Reliability Entity (TRE), SERC Reliability Corporation (SERC), Florida Reliability Coordinating Council (FRCC), ReliabilityFirst Corporation (RFC), and Northeast Power Coordinating Council (NPCC).

electricity generation between present and future has the largest impact on L.H2 FCETs, primarily because of the dominance of electricity for liquefaction in overall (WTW) energy consumption of L.H2 FCETs.

In terms of regional variations, the air emissions reduction potential is relatively higher for WECC (Western Electricity Coordinating Council), which encompasses California, where most of the current

FCET demonstration and deployment activities are occurring in the United States. In the RFC (ReliabilityFirst Corporation) region, WTW CO emissions increase between 2016 and 2035, deviating from the general pattern (decrease in emissions over time) for other air pollutants and regions in Figure 6. The main cause is the significant decrease of coal in the share of electricity generation fuels in the RFC region, from 43.8% in 2016 to 30% in 2035, coupled with much higher contribution of natural gas (from 20.4% to 40%) in the same time frame. For the same electricity output (per kWh), the national average fleet of natural gas power plants emits more CO than the fleet of coal-based units does, although a typical natural gas combined cycle (NG-CC) unit creates less CO emissions compared to a coal-fired steam turbine counterpart [32].

Figures 5 and 6 clearly show why it is important to consider the impact of electricity consumption related to compression and liquefaction for life-cycle analysis of hydrogen FCETs, accounting for regional electric grids and their evolution over time. In terms of spatial variation (for 2016), regional WTW air emissions results for FCETs can deviate by 7% for GHGs, 3% for VOCs, 13% for CO, 9% for NOx, 10% for PM2.5, and 56% for SOx. With regard to temporal (current and future) evolution of electricity generation mix and emissions factors, the variation in life-cycle results of FCETs relative to national averages can be 7% for GHGs, 7% for VOCs, 13% for CO, 28% for NOx, 22% for PM2.5, and 45% for SOx. Note that benefits of FCETs to air quality may exceed those implied by life-cycle emissions reductions, because indirect upstream emissions in SMR and electric power plants occur in less populated areas. In contrast, direct tail-pipe emissions may occur in populated urban areas, resulting in increased exposure to pollutants, and more significant impacts on human health.

5. Comparison with Other Potential Technological Advances

The results shown thus far indicate that FCETs can produce numerous life-cycle benefits over conventional diesel trucks by reducing petroleum use, GHG emissions, and criteria air pollutants emissions on a WTW basis. In addition to those baseline WTW comparisons, it is also desirable to examine how the two truck technologies (diesel vs. fuel cell electric) compare in the context of potential technological advances. In this section, therefore, we evaluate the impact of vehicle technology improvements (other than electrification) for conventional diesel trucks, as well as renewable hydrogen production technology for FCETs.

Key non-electric advanced vehicle technologies for conventional diesel trucks include thermal efficiency improvement of diesel engines, lightweighting, aerodynamic drag reduction, and lower rolling resistance tires [5, 36, 37, 38, 39]. However, except diesel engine's brake thermal efficiency improvement, it is likely that the other three technologies (e.g., lower rolling resistance tires) will also be adopted for FCETs. Therefore, for diesel trucks, we focus on diesel engine's brake thermal efficiency improvement, which is exclusively applicable to diesel trucks. In fact, among various near- and long-term vehicle technologies (other than electrification) for diesel trucks, brake thermal efficiency improvement has the potential to bring the largest reduction in fuel consumption [36]. As for renewable hydrogen fuel production technology for FCETs, we evaluate water electrolysis via solar power. In general, renewable hydrogen fuel production technology, particularly solar/wind electrolysis, is believed to produce the largest reduction of WTW fossil fuel consumption and air emissions associated with hydrogen use in fuel cell electric vehicles, including FCETs.

Overall, the comparison between conventional diesel and fuel cell electric trucks in this section is focused on one of the most promising ongoing and future technological advances for each of diesel and fuel cell electric trucks. For illustration, three types of trucks are considered: GVWR Class 6 straight box trucks, Class 8b typical combination short-haul trucks, and Class 8b drayage trucks. The main difference between typical combination short-haul trucks (or tractor-trailers) and drayage trucks is the operating conditions (e.g., relative significance of highway vs. urban and local driving; see Table 1).

Regarding advanced (non-electric) vehicle technologies for trucks, previous studies have touched on load reduction (e.g., lightweighting) and engine efficiency improvement [40, 41, 42]. However, those studies do not compare non-electric advanced vehicle technologies with the hydrogen FCETs on a WTW basis, nor do they incorporate renewable hydrogen production pathways such as solar electrolysis. Therefore, our analysis (in this section) aims to put the WTW results of FCETs into a broader context, incorporating potential advances in vehicle and fuel production technologies, which were not addressed in the existing literature. We recognize that the WTW impacts (or overall benefit) of the advanced vehicle technologies vary with duty cycle [40, 42], and may also depend on the interaction between the technology and other components [40]. For a more detailed analysis, in-depth vehicle and/or component design must be done [43], but this is left for future work.

To evaluate the aforementioned technological advances and potential, we used the same suite of data, methods, and models discussed previously, except that we employ FASTSim [44] for a vehicle dynamic simulation instead of Autonomie (due to its availability). Baseline diesel truck specifications are based on the recent Ricardo-ICCT report [22] on GVWR Class 6 medium-duty straight box trucks and Class 8b heavy-duty combination trucks (or 18-wheelers). On top of the baseline diesel trucks, we applied 10%

diesel engine peak efficiency improvements (e.g., 42% to 52%), and estimated an incremental change in fuel consumption and WTW results, repeating the overall process depicted in Figure 1. In addition, as mentioned earlier, fuel consumption (or fuel economy) ratios—rather than absolute values—are used from the vehicle dynamic simulation for implementation in GREET (Figure 1). Due to the lack of reliable data quantifying changes in CAP emissions with engine brake thermal efficiency change, this analysis only evaluates WTW energy consumption and GHG emissions.

Figure 7 shows the WTW results of fossil fuel consumption and GHG emissions for three vehicle types: medium-duty box trucks, (typical) heavy-duty combination short-haul trucks, and heavy-duty drayage trucks. For FCETs, the transition from the baseline central SMR pathway to solar electrolysis for hydrogen fuel production reduces fossil fuel consumption by 90% and GHG emissions by 86% on a WTW basis, regardless of GVWR class, truck type, or vocation. The remaining 10% of WTW fossil fuel use and 14% of WTW GHG emissions for solar electrolysis pathway are attributable to the grid electricity used for hydrogen compression at refueling stations.

The WTW benefit of the brake thermal efficiency improvement (e.g., 42% to 52%) for conventional diesel trucks is estimated to be around 20%. For Class 6 box trucks, the 20% reduction benefit of brake thermal efficiency improvement for diesel trucks is not enough to edge out the benefit of baseline FCETs. Class 6 diesel-powered box trucks with improved brake thermal efficiency consume 14% more fossil fuel and create 38% more GHG emissions than their baseline FCET counterparts. In case of Class 8b drayage trucks, diesel trucks with improved brake thermal efficiency consume 2% less fossil fuel than the baseline FCETs, but emit 18% more GHG emissions on a WTW basis. For Class 8b (typical) combination short-haul trucks, engine efficiency improvement benefit is relatively large: 20% less WTW fossil fuel consumption and 4% less GHG emissions compared to baseline FCETs. The results imply that the relative benefit of advanced diesel truck technologies over baseline FCETs varies with GVWR class, truck type, and vocation. In addition, even when compared with the aggressive brake thermal efficiency improvement for conventional diesel trucks, (baseline) FCET technology produces a robust benefit by reducing WTW fossil fuel consumption and GHG emissions over diesel counterparts, particularly in urban and local operating conditions (e.g., Class 6 box trucks and Class 8b drayage trucks). However, as the share of highway driving increases, the reductions in fossil fuel consumption and GHG emissions may diminish, as exemplified by typical combination short-haul trucks (Figures 7c and 7d).

From Figure 7, it is also evident that the potential diesel engine efficiency improvement brings notably smaller benefit compared to solar electrolysis technology for FCETs, regardless of truck types or

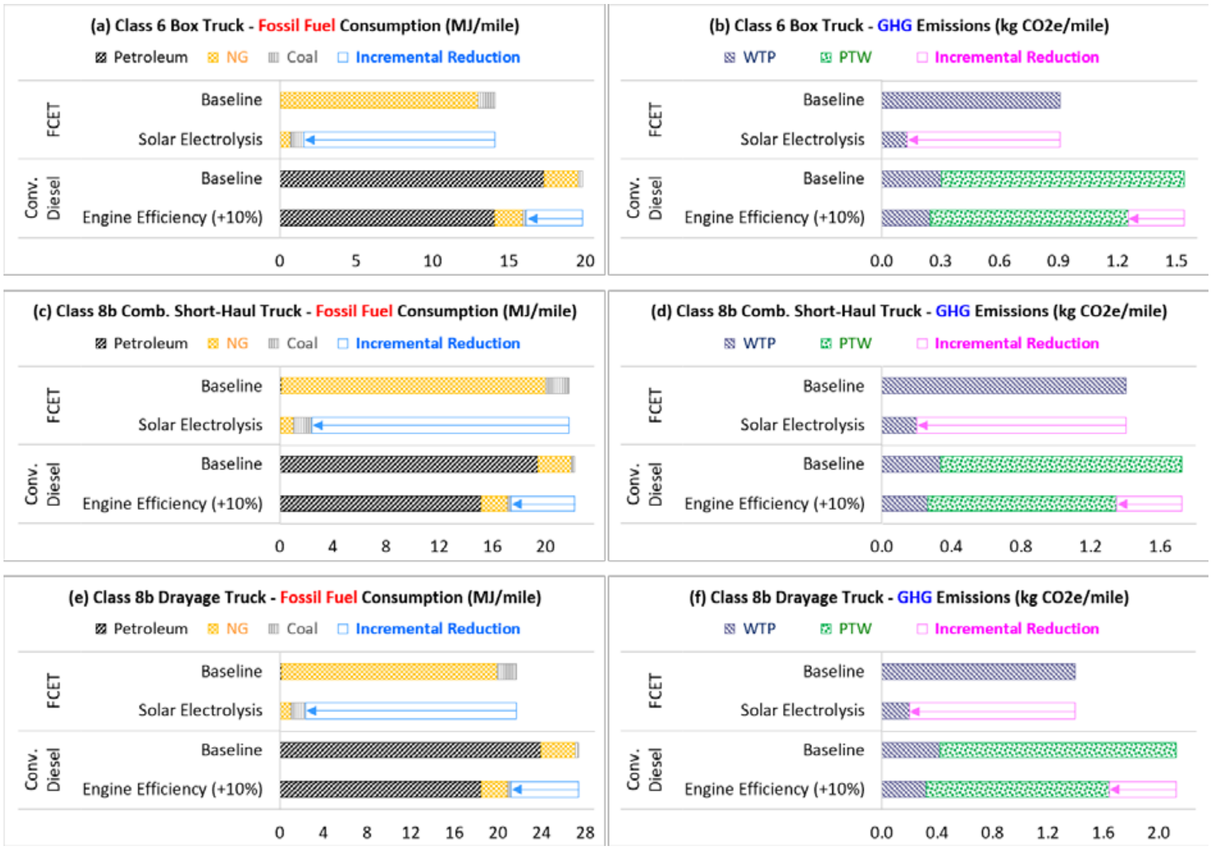


Figure 7. WTW fossil fuel consumption and GHG emissions of hydrogen (G.H2) FCETs in comparison with conventional diesel trucks—baseline vs. engine brake thermal efficiency improvement for diesel trucks and renewable hydrogen fuel production technology (solar electrolysis) for FCETs. Class 8b combination short-haul trucks refer to typical operation (about 50/50 split between highway and urban driving), whereas drayage trucks operate mostly on urban or local roads.

vocations. In other words, despite the aggressive improvement of diesel engine's brake thermal efficiency or other advanced vehicle technologies (except electrification), conventional diesel trucks may reach a limit at some point in terms of reducing fossil fuel use and air emissions. On the other hand, owing to the renewable hydrogen fuel production technologies, including solar electrolysis, FCETs have a greater potential to cut fossil energy consumption and air emissions, beyond the diesel trucks' technological limit.

6. Conclusions

Based on the ensemble of well-established methods and high-fidelity vehicle dynamic simulations, this study shows that hydrogen FCET technology can provide numerous benefits over conventional diesel trucks. Switching from conventional diesel to FCETs would reduce life-cycle fossil fuel consumption, GHG emissions, and air pollutants emissions.

Compared to conventional diesel trucks, hydrogen FCETs could nearly eliminate petroleum energy consumption on a per-vehicle basis. However, they may shift the primary energy source from petroleum to natural gas, because hydrogen is produced via SMR of natural gas (in the baseline scenario). The electricity required to compress hydrogen for G.H2 and to liquefy hydrogen for L.H2 add energy and emissions burdens for FCETs. Because of the significance of electricity use (for compression and liquefaction) in overall WTW FCET energy consumption, variations in regional electricity generation mix can be important for WTW results of FCETs.

When competing with non-electric advanced vehicle technologies, particularly brake thermal efficiency improvements for conventional diesel trucks, the benefits of FCETs remain robust, especially for the urban and/or local driving conditions in which most of the FCETs would be deployed in the near term. In addition, renewable-based hydrogen fuel production technologies (e.g., solar electrolysis) can greatly improve the overall benefit of FCETs, far exceeding the potential energy use and air emissions reductions that near- and long-term advances in (non-electric) diesel truck technologies can realize.

Several improvements can be made to further advance life-cycle studies of FCETs. First, this study adopted the most recent EPA/NHTSA test cycles and composite fuel consumption estimation methods, but more diverse duty cycles or operating conditions may be considered, especially because the medium- and heavy-duty vehicle sector is very diverse in terms of vehicle types and applications. Second, in addition to the comparison with the conventional diesel trucks, other technologies (e.g., biodiesel, diesel hybrid-electric, compressed natural gas) could be compared with the FCETs. Third, for comparison with the non-electric advanced vehicle technologies for conventional diesel trucks, evaluating the impact of CAP emissions in addition to energy use and GHG emissions could also be meaningful. Fourth, a more comprehensive analysis incorporating other hydrogen pathways (e.g., biomass gasification) is needed. Last, further investigation is required to assess the WTW benefits of FCETs to air quality improvement, beyond the WTW emissions inventory developed in this analysis.

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