Title

A Comparative Review of Hydrogen Engines and Fuel Cells for Trucks

Authors

Wang, Guihua
Fulton, Lewis

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Technical Report

Guihua Wang and Lewis M. Fulton

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Abstract

The concept of hydrogen internal combustion engine vehicles (ICEVs) is not new, but has gained renewed interest lately, especially for heavy-duty trucks. Different from hydrogen fuel cell electric vehicles (FCEVs), which represent a novel zero-emission technology, hydrogen engines are modified conventional engines running on hydrogen fuel instead of gasoline or diesel. This study presents a comparative review of hydrogen engines and fuel cells, based on existing reports and discussions with industry. We consider aspects such as vehicle efficiency, greenhouse gas (GHG) and criteria pollutant emissions, hydrogen fuel purity, vehicle attributes, vehicle acquisition costs, total costs of ownership, and new policies. We find that hydrogen ICEVs offer some advantages and disadvantages: advantages include lower production cost and potentially greater reliability; disadvantages include potentially overall lower efficiency (and thus higher fuel cost) and lack of zero-vehicle-emission operation. While the technologies could be complementary (e.g., hydrogen ICEVs serving as a transition technology toward FCEVs), they also may compete, with success for hydrogen ICEVs resulting in setbacks for FCEV market success.

Keywords: Hydrogen internal combustion engine vehicle; Fuel cell electric vehicle (FCEV); Heavy-duty vehicle (HDV); Zero-emission vehicle (ZEV); Total cost of ownership (TCO)

Contents

1. Introduction

Recently, the concept of hydrogen internal combustion engine vehicles (ICEVs) has gained renewed interest, especially for medium- and heavy-duty trucks. Hydrogen ICEVs can operate on hydrogen via combustion, much like a conventional diesel or gasoline engine vehicle. They do not use a fuel cell, which would result in some disadvantages but also some advantages. This study summarizes findings from the available literature on hydrogen engines, as compared to hydrogen fuel cells, for trucking applications, including aspects such as vehicle efficiency, greenhouse gas (GHG) and criteria pollutant emissions, hydrogen fuel purity, vehicle attributes, vehicle acquisition costs, total costs of ownership (TCOs), and new policies in the U.S. and the European Union (EU).

2. What is a hydrogen engine?

Hydrogen engines are modified internal combustion engines (ICEs) which run on hydrogen fuel instead of gasoline or diesel. Since gasoline and diesel ICEs have long been used in on-road transportation, hydrogen ICEs involve familiar parts and technology for vehicle manufacturers and fleet operators, and can take advantage of existing production systems and scale economies. Hydrogen engines convert chemical energy in the fuel to mechanical energy, through the combustion process, while fuel cells convert chemical energy directly to electrical energy, through the electrochemical reactions. As compared to ICEs, hydrogen fuel cells are a new, very different, advanced technology, and still in nascent market with resulting high costs.

3. Vehicle efficiency and fuel economy

With current technology, hydrogen ICEVs have a typical efficiency from tank to wheels of 40-45%, as compared to 50-60% for hydrogen fuel cell electric vehicles (FCEVs). U.S. EPA's recent regulatory cost analysis assumed that FCEVs have an average efficiency of 53%, while hydrogen ICEVs have an efficiency of 42% (U.S. EPA, 2024a). It is worth noting that battery electric vehicles (BEVs) typically have an approximately 80% efficiency.

Current studies generally consider hydrogen ICEVs to have a slightly lower efficiency or fuel economy than their diesel counterparts. Hydrogen engines could use spark-ignition or compression-ignition, although the efficiency in both cases is lower than for diesel engines (Srna, 2023; Babayev et al., 2022). The spark-ignition technology is likely to be introduced to the market earlier, and the compression-ignition technology may come to the market later as it has an efficiency advantage (Srna, 2023). With advanced compression-ignition technologies, hydrogen ICEVs could have a brake thermal efficiency marginally lower than that of the diesel vehicles (Babayev et al., 2022).

A recent International Council on Clean Transportation (ICCT) study estimated the TCO of alternative powertrain technologies for Class 8 long-haul trucks in the U.S. The study used a 44% peak efficiency for hydrogen ICEs, a 60% peak efficiency for FCEVs, and a 46% peak efficiency for diesel trucks, with current (2022) technologies (Basma et al., 2023). Efficiencies are shown in Table 1, which also presents the projected future (2035) efficiency improvements, along with needed hydrogen storage tank sizes.

Table 1. Current and future Class 8 long-haul tractor-trailer truck efficiency and hydrogen storage size (Basma et al., 2023)

	Current (2022)	Future (2035)
Peak efficiency (diesel)	46%	55%
Peak efficiency (H2 ICE)	44%	50%
Peak efficiency (FCEV)	60%	67%
H2 tank size (H2 ICE)	76 kg	52 kg
H2 tank size (FCEV)	62 kg	40 kg
Average daily mileage	500 miles	500 miles

The peak efficiencies shown in Table 1 are not necessarily achieved under the same operating conditions for the different technologies. Hydrogen engines and fuel cells reach their higher efficiency at different load levels, as shown schematically in Figure 1, a Bosch figure cited in Richter and Graf (2021). FCEVs are more efficient at low loads. It is common that the fuel cell needs to be oversized for a truck to maximize efficiency. Thus, fuel cells are best in smaller, lower-power applications. In comparison, engines become more efficient at high loads, which is an incentive for engine downsizing in diesel vehicles or hydrogen ICEVs. Put another way, the most efficient operating mode for ICEVs is to downsize the engine and make it work harder. Hydrogen ICEs are best for very large vehicles, construction machinery, or agricultural applications. Looking at the power output in Figure 1, as it increases towards 100%, the efficiency gap between fuel cell and hydrogen ICE decreases, and they might even cross over in some very high power applications, e.g., excavators which operate near 100% load most of the time.

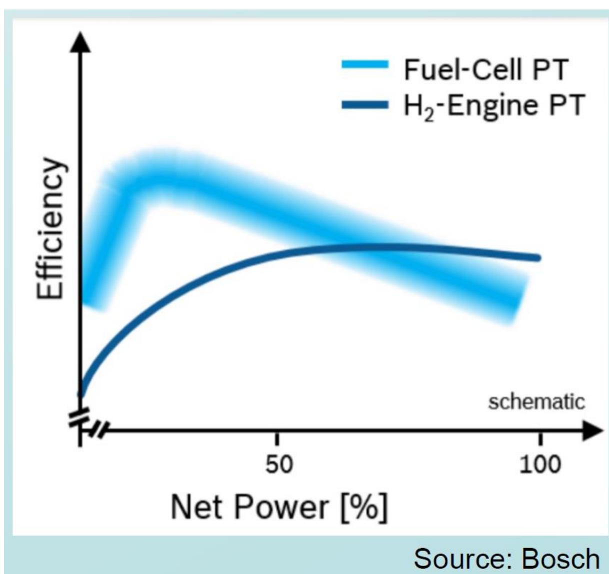

Figure 1. Hydrogen engine and fuel cell reach higher efficiency at different load levels

Similarly, Figure 2 shows powertrain technologies have different efficiency properties under low and high loads (Heid et al., 2021). The powertrain technologies include hydrogen FCEVs, hydrogen ICEVs, diesel ICEVs, and BEVs. The efficiency vs. load findings are similar to those shown in Figure 1. Figure 2 also suggests that, under high loads, hydrogen ICEVs may likely have slightly better efficiency performance than FCEVs.

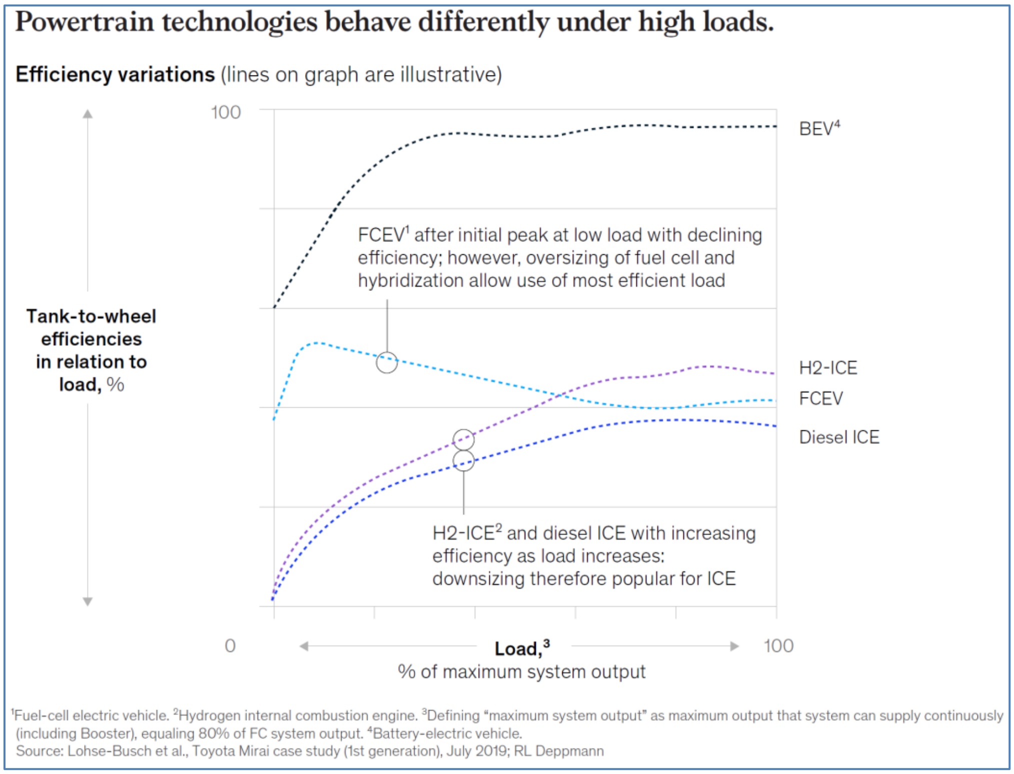

Figure 2. Powertrain technologies behave differently under high loads from a vehicle efficiency perspective (Heid et al., 2021)

Like other internal combustion engines, a hydrogen engine will not exhibit much reduction in efficiency as the engine ages, but a fuel cell will show reduced efficiency and performance with age, and this efficiency reduction could be significant over many years unless the fuel cell stacks are refurbished or replaced (Hydrogen Insight, 2023). Apart from efficiency decline with age, fuel cells typically have a lifespan of 5 to 10 years, depending on the application, and then the membrane electrode assembly (MEA) wears out (Ballard, 2023). Thus, there is a need to refurbish the fuel cell stack, which also provides an opportunity for putting in the latest MEA technology, while reusing the plates and hardware (Ballard, 2023).

Figure 3 shows current and future Class 8 long-haul tractor-trailer truck fuel economy, in miles per gallon (mpg) diesel equivalent. Truck fuel economy for those vehicle technologies was simulated under the National Renewable Energy Laboratory (NREL) long-haul cycle at a reference payload of 38,000 lbs. (Basma et al., 2023). With current (2022) technologies, fuel economy is 6.8 mpg for diesel trucks, 7.4 mpg for fuel cells, and 6.0 mpg for hydrogen engines.

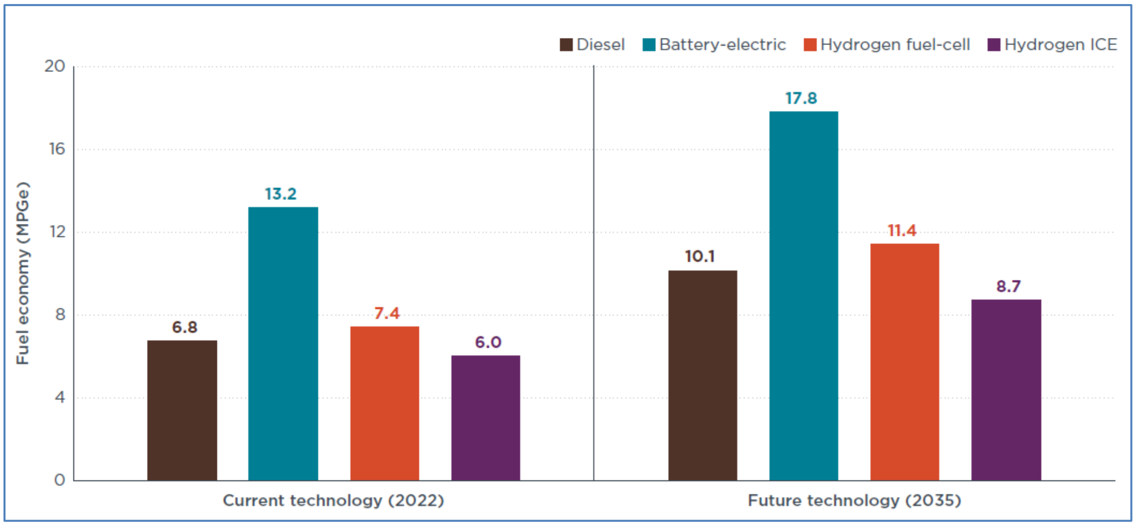

Figure 3. Current and future Class 8 long-haul tractor-trailer truck fuel economy, in miles per gallon diesel equivalent (Basma et al., 2023)

Some of the FCEV advantage in fuel economy is due to the hybridized powertrain and, similarly, hybridized hydrogen ICEVs could deliver improved fuel economy as well, indicated by the Southwest Research Institute (CARB, 2023a). However, complexity makes it highly if hydrogen ICE hybrids are a promising option.

4. Hydrogen fuel purity

Hydrogen engines have a much higher tolerance to lower purity hydrogen than do fuel cells (Srna, 2023). Based on the International Organization for Standardization (ISO), the purity limit for fuel cells is 99.97% H_2, with non-hydrogen gases being lower than 0.03%, while hydrogen engines can run with a 98% H_2 purity limit, with non-hydrogen gases being lower than 2% (Wróbel et al., 2022). It appears likely that this somewhat lower-purity hydrogen fuel could be less expensive to produce and distribute through the hydrogen supply system, though this will depend on how it is made and transported. Hydrogen engine vehicles fueled with lower-purity hydrogen might in turn save on fuel costs due to the potentially lower fuel price (though fuel cost per mile will also depend on vehicle efficiency). Thus, fuel purity could have an impact on the TCO. However, we have not found any estimates of the potential hydrogen price or TCO differences in the literature.

It should also be noted that a hydrogen supply system designed to meet the lower purity standard would then be uncertified to provide hydrogen for FCEVs. Thus, a decision on the level of purity through the system is also a decision whether to restrict the system to ICEVs or, with the higher purity standard, allow for FCEVs to operate as well.

5. Emissions

Zero-emission vehicles (ZEVs) are defined as vehicles that have no tailpipe emissions of air pollutants or GHGs (Basma et al., 2023; CARB, 2019). All vehicles, including ZEVs, produce emissions; e.g., all ZEVs produce particulate emissions from tire wear and brake wear, and ZEVs have air conditioning units which may result in GHG emissions from leakage (U.S. EPA, 2024a). In the U.S., the current ZEV technologies include BEVs and hydrogen FCEVs (CARB, 2024a). Hydrogen combustion in the engine is not a zero-emission process, so technically hydrogen ICEVs are not ZEVs.

The main pollutant emission from hydrogen ICEVs is NO_x. Hydrogen ICEs emit NO_x in the exhaust, although the NO_x could be reduced to near zero with aftertreatment. Raw NO_x emissions from hydrogen engines are already reduced by a factor of 10 approximately, compared to a typical diesel engine; actually, hydrogen ICEs can fulfill current EURO6 regulation with no aftertreatment, indicated by Sandia National Laboratories (CARB, 2023a).

The exhaust aftertreatment components of a diesel powertrain contain diesel oxidation catalyst (DOC), diesel particulate filter (DPF), and selective catalytic reduction (SCR). A hydrogen ICEV fueled with neat H_2 only requires DOC and SCR to reduce NO_x, but the SCR system will be smaller for the hydrogen ICEV than a comparable diesel vehicle because the engine-out NO_x emissions are lower (U.S. EPA, 2024a).

Hydrogen ICEVs have a very low carbon footprint, but are not a technology with zero carbon tailpipe emissions. The CO_2 sources of hydrogen ICEVs include lube oil consumption (typically 0.05% of diesel consumption in a diesel truck), carbon content of urea (CH_4N_2O) used in SCR, and carbon compounds in fuel (e.g., <100 ppm CH_4), indicated by Daimler Truck (CARB, 2023a).

Some literature loosely refers to hydrogen ICEs as a technology having zero carbon emissions at the tailpipe, which is incorrect. Hydrogen ICEs could help move towards carbon neutrality as operating hydrogen ICEVs results in very low carbon emissions. (Note that, from a fuel cycle standpoint, the net impact on GHG emissions depends on how hydrogen is made, stored, distributed, consumed, etc. Clearly, the fuel cycle perspective applies to any form of energy, including electricity.)

Hydrogen ICEVs emit many species of pollutants, just like conventional gasoline or diesel vehicles. This is mainly driven by the fact that a small fraction of the lubricant can get into the combustion chamber and burn. The exhaust can contain some of the lube oil and its combustion products. Typically, very small quantities of CO, CO_2, HC, and PM can be found in the exhaust gas (Kim, 2023; Falfari et al., 2023).

In addition, hydrogen ICEVs emit trace N_2O. N_2O is primarily formed in the exhaust aftertreatment system, such as hydrogen reaction with NO over noble metal catalyst, NH_3 oxidation in SCR, and other processes, indicated by Sandia National Laboratories (CARB, 2023a). There is also NH_3 slip through catalyst, indicated by Sandia National Laboratories (CARB, 2023a).

There is also H_2 slip in the exhaust of hydrogen ICEVs. A Society of Automotive Engineers (SAE) paper revealed that the highest indicated efficiency (close to 47%) coupled with low NO_x and acceptable unburned H_2 emissions (respectively below 0.5g/kWh and 1% input energy) was obtained at lean mixture and early hydrogen injection (Rouleau et al., 2021).

Due to the very small size of the H_2 molecule, H_2 is able to leak through many solid materials into the air, and hydrogen can also get into the metal lattice and cause fatigue, which is called hydrogen embrittlement (Hydrogen Tools, 2024). Escaped hydrogen gas mixed with air is, at high concentrations, potentially explosive. H_2 leakage from the vehicle, as well as how this would be different between hydrogen ICEs and fuel cells, is not well reported in the literature. Leakage throughout the hydrogen supply system could be ranging from a few percent up to 10%, but this is generally unrelated to vehicle drivetrain type.

6. Vehicle attributes

Cummins has shown a proof-of-concept medium-duty truck powered by a hydrogen engine. The hydrogen engine delivers 290 hp (216 kW), similar to its equivalent diesel engine (Autoevolution, 2023). Cummins used regular diesel driveline components in its prototype, which brought in familiar parts and technology and thus is another advantage over competing zero-emission solutions (Autoevolution, 2023). The hydrogen storage system comprises 700-bar pressure high-capacity tanks reinforced with carbon fiber, allowing a 310-mile range (Autoevolution, 2023). Cummins' twin hydrogen fuel tanks have a combined capacity of around 40 kg, with additional space on the chassis for an auxiliary 10 kg tank (The Engineer, 2023). Cummins' hydrogen truck can be refueled in as little as 10 minutes (The Engineer, 2023).

As shown in Table 1, for Class 8 long-haul tractor-trailer trucks, with an average daily mileage of 500 miles, the current hydrogen tank size is 76 kg for hydrogen ICEVs and 62 kg for FCEVs, and the power is 339 kW for both powertrain types (Basma et al., 2023). A hydrogen ICE line-haul truck with the 500-mile range will take 32 minutes to fast fill its hydrogen tank from empty to full, indicated by a presentation by Cummins (Cummins Inc., 2023a).

Volvo is developing hydrogen ICE trucks and plans to commercialize them by 2030 (Volvo Trucks, 2024). Its hydrogen engines will allegedly feature High Pressure Direct Injection (HPDI), where a small amount of ignition fuel is injected with high pressure to enable compression ignition before hydrogen is added. This technology with compression ignition has high energy efficiency and increased engine power.

Durability of hydrogen ICE technology will eventually be comparable to current diesel engines.

Typically, hydrogen engines are designed to use more air than theoretically required for complete combustion. To have the same power output, hydrogen engines are usually larger than gasoline engines, or are equipped with turbochargers or superchargers (College of the Desert, 2001).

7. Cargo payload and capacity penalty

Fuel cells and hydrogen engines require large hydrogen storage tanks onboard, which leads to a penalty in cargo payload and capacity, compared to diesel truck counterparts. U.S. EPA (2024b) assessed and concluded that most heavy-duty vehicles have sufficient physical space to package gaseous hydrogen storage tanks onboard for fuel cell applications, which also remains the case for long-haul sleeper cabs if they refuel one time en route. There is no literature available to distinguish the payload and capacity penalty between hydrogen ICEVs and FCEVs. The need for additional hydrogen storage would depend on the expected efficiency and required range of these trucks. FCEVs tend to have less penalty in payload and capacity than hydrogen ICEVs, as FCEVs are expected to have higher fuel economy or efficiency so their needed hydrogen tank size is smaller, as shown in Table 1 and Figure 3.

In fact, batteries and hydrogen both require sacrifices on payload and capacity, and the penalty is even more pronounced for BEVs. This is mainly driven by the fact that batteries are heavy. Trucks with batteries matching the range of fuel cells (particularly a 500-mile range or more) are generally seen as likely to be significantly heavier, due to large kWh of battery capacity required (and associated weight). For benchmarking, Tesla delivered its first Class 8 electric truck to food and drink giant PepsiCo, which it claims can travel 500 miles (805km), on one charge of its massive 1 MWh battery (Autoweek, 2022; Hydrogen Insight, 2023). Truck simulations using present lithium battery technology with a pack energy density of 170 Wh/kg indicated that for a range of 600 miles, the battery pack would need to store about 1200 kWh, weigh 6300 kg, and have a volume of 2700 L (Burke, 2022).

Vehicles that are particularly constrained on cargo payload or capacity may be limited to more energy-dense liquid fuels such as diesel, biofuels, or liquid hydrogen.

8. Vehicle costs

Theoretically, in the very long run, capital costs of hydrogen ICEVs at mass production could be largely identical to diesel trucks. They may be even less expensive than diesel trucks if the lower exhaust treatment requirements can offset the added costs for onboard hydrogen tanks and others. However, this is a very optimistic and unlikely scenario and almost all existing studies expect a higher cost for hydrogen ICEVs than their diesel counterparts.

Compared to fuel cells, hydrogen ICEs have a low upfront cost, with 2025 technology (Srna, 2023). By 2030, fuel cell upfront cost could be comparable to that of hydrogen ICEs, given technology advances and scale of production (Srna, 2023; Vijayagopal and Rousseau, 2023).

There are limited studies involving hydrogen ICEV costs. Table 2 summarizes vehicle purchase costs from studies and compares the hydrogen ICEV cost with other powertrain technologies. Clearly, a hydrogen

ICE truck currently would incur a 1.4 to 1.7 times higher retail price or manufacturing cost than its diesel counterpart; the price is expected to decline to about 1.3 times higher than diesel by 2030 and, at that time, the hydrogen ICEVs and FCEVs likely reach purchase price parity.

Table 2. Summary of vehicle purchase costs from studies

	Cummins, long-haul, 500-mile range	**ANL**, long-haul, 500-mile range, mass production volume		**ICCT**, long-haul, 500-mile average daily mileage		
Technology	Purchase price, **2027**	Manufacturing cost, **2021** tech	Manufacturing cost, **2030**, BAU tech	Retail price, **2022**	Retail price, **2027**	Retail price, **2030**
Diesel ICEV	1x	1x	1x	1x	1x	1x
H2 ICEV	1.5x	1.4x	1.2x	1.7x	1.5x	1.3x
FCEV	2x	2.2x	1.3x	2.8x	1.9x	1.3x
BEV	2.2x	2.3x	1.6x	2.3x	1.6x	1.2x

Of the studies in Table 2, Cummins forecasted the purchase price of a line-haul hydrogen ICE truck, with the 500-mile range, by 2027. The study assumes a hydrogen ICE truck drives 120,000 miles/year, with fuel economy of 9 mpg diesel equivalent or 8 miles/kg hydrogen, and this line-haul truck will take 32 minutes to fast fill its hydrogen tank from empty to full, indicated by a presentation by Cummins (Cummins Inc., 2023a).

The Argonne National Laboratory (ANL) study estimated the manufacturing cost for Class 8 long-haul hydrogen ICE trucks, with the 500-mile range and an annual mileage of 100,000 miles/year (Vijayagopal and Rousseau, 2023). The study also estimated vehicle costs for the 2030 business-as-usual (BAU) level of technology progress. The results in Table 2 correspond to the assumption that the production volume is 100,000 units or more, so the low volume production cost multiplier becomes 1 (otherwise, 1.75).

Figure 4 shows the ICCT-forecasted retail price evolution of Class 8 long-haul tractor-trailers for diesel, battery electric, fuel cell, and hydrogen ICE trucks between 2022 and 2040, with an average daily mileage of 500 miles (Basma et al., 2023). The results for a few years (2022, 2027, and 2030) were extracted and transformed for comparison in Table 2. Figure 4 also shows that hydrogen ICEVs will never reach price parity with diesel by 2040.

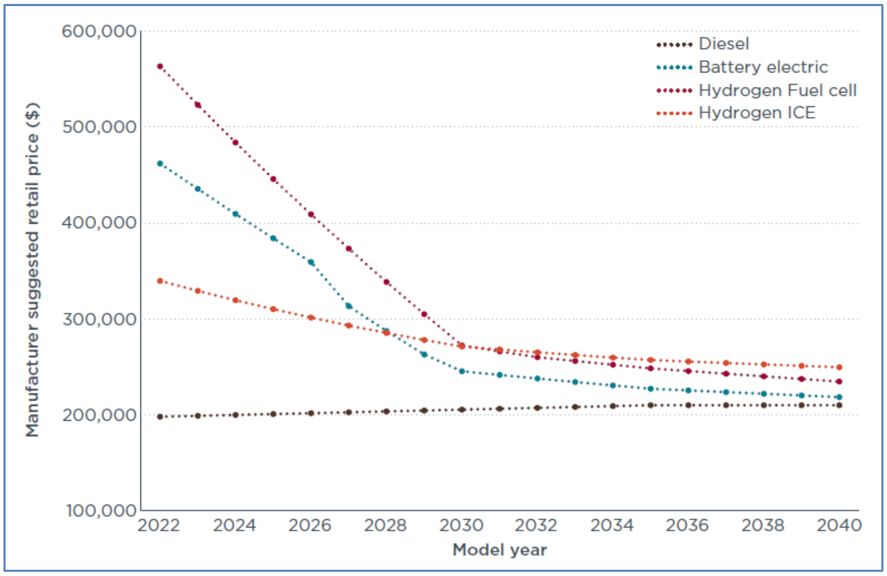

Figure 4. Retail price evolution of Class 8 long-haul tractor-trailers for diesel, battery electric, fuel cell, and hydrogen ICE trucks (Basma et al., 2023)

9. Total cost of ownership (TCO)

Generally, fuel cells have a TCO advantage over hydrogen engines for on-road transportation, as fuel cell efficiency advantage plays an important role (Srna, 2023). Table 3 shows a summary of TCO from two studies and both indicate that FCEVs will have a better TCO than hydrogen ICEVs by 2030. This will always depend on vehicle technology and price assumptions, as well as fuel price assumptions.

Table 3. Summary of TCO from studies

	ANL study	ICCT study
Technology	TCO, **2030**, BAU tech	TCO, **2030**, California
Diesel ICEV	1x	1x
H2 ICEV	1.3x	1.5x
FCEV	1.1x	1.3x
BEV	N.A.	1.0x

The ANL study estimated the TCO for Class 8 long-haul hydrogen ICE trucks, with the 500-mile range, 100,000 miles/year, a vehicle lifetime of 15 years, a discount rate of 5%, $4/gallon diesel, and $4/kg hydrogen, at high volume vehicle production (Vijayagopal and Rousseau, 2023).

The ICCT study estimated the TCO for Class 8 long-haul tractor-trailers for diesel, battery electric, fuel cell, and hydrogen ICE trucks between 2022 and 2040. It estimated national and state specific TCOs in the U.S., from a perspective of the first ownership period of 5 years. This assumes approximately 120,000 miles/year, a discount rate of 7%, an average daily mileage of 500 miles, and green hydrogen fuel price as input (Basma et al., 2023).

From a spatial perspective, many costs for trucks of a given technology should be similar around the U.S., though fuel prices may vary. The renewable (green) hydrogen price is likely to vary around the U.S., given varying solar and wind resources (Basma et al., 2023). From a temporal perspective, the same ICCT study used the following green hydrogen prices for California showing a declining trend over time: $11.6/kg (2023), $10.3/kg (2030), and $9.6/kg (2040). Figure 5 shows the ICCT study's TCO of Class 8 long-haul tractor-trailers for different truck technologies, for truck model years 2022 and 2030 in California.

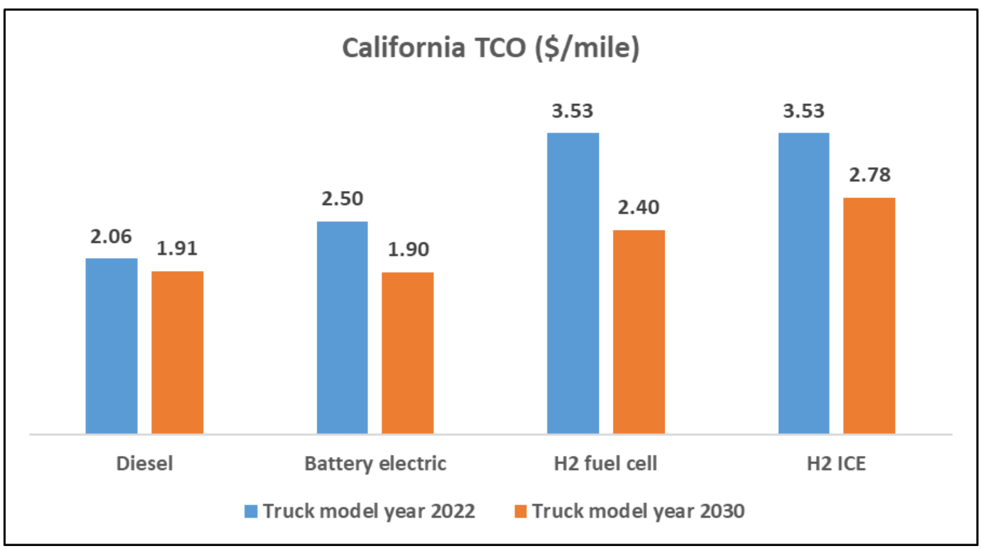

Figure 5. TCO of Class 8 long-haul tractor-trailers for different truck technologies, for truck model years 2022 and 2030 in California. Data from Basma et al. (2023).

Figure 6 shows a TCO comparison for off-road dump trucks in a mining application (Heid et al., 2021). For such off-road applications, hydrogen ICEs might have a slightly better TCO than fuel cells in the long run although the results depend heavily on cost modeling assumptions.

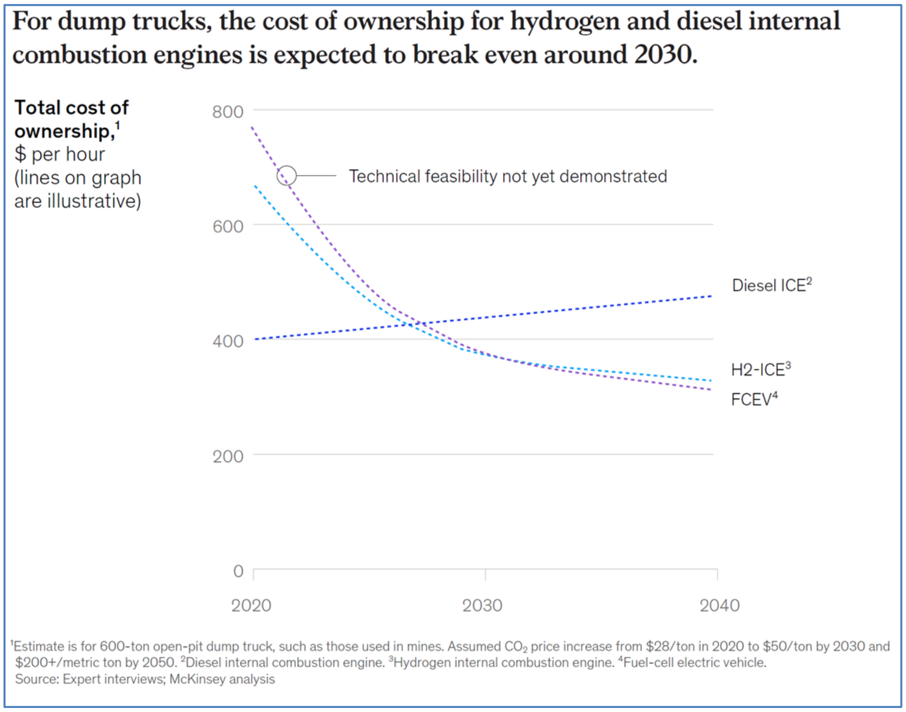

Figure 6. TCO comparison for off-road dump trucks in a mining application (Heid et al., 2021)

10. Other differences between hydrogen engines and fuel cells

In addition to the comparisons discussed earlier, other differences between hydrogen engines and fuel cells include, but are not limited to, the following:

- Fuel cells run quiet as they have fewer moving parts (U.S. DOE, 2023).
- Fuel cells are sensitive to vibration and dust; hydrogen engines are robust in vibration or dusty environments, e.g., in construction or agriculture applications (Srna, 2023; Cummins Inc., 2022).
- Fuel cells need more noble metals, such as platinum (Srna, 2023).
- Fuel cells have a high cooling need which is critical for stationary and slow-moving applications (Srna, 2023).
- Engines including hydrogen engines are easy to start in cold-weather applications (Srna, 2023).

11. Hydrogen engines and fuel cells are complementary technologies with possible conflicts

Hydrogen engines and fuel cells are two complementary technologies, as they exist and develop in the same hydrogen ecosystem (Cummins Inc., 2023b); however, both technologies may have possible conflicts in investment and market.

Both technologies are facing the same major challenges of hydrogen economy: lack of availability or development of hydrogen refueling infrastructure and hydrogen onboard storage. If original equipment manufacturers (OEMs) and tank suppliers are provided with an opportunity to amortize research and development (R&D) and capital expenditure (CAPEX) over a larger number of vehicles (i.e., both hydrogen ICEVs and FCEVs), that will help bring down the cost curve for all hydrogen vehicles and support the competitiveness of both solutions.

One particular case of complementarity is where fuel cells are not a viable solution, e.g., in cold-weather applications, hydrogen ICEs can be used. Hydrogen engines are robust in vibration or dusty environments, so they may have a role in construction or agriculture applications where fuel cells are not ideal.

In the face of combating climate change, achieving the carbon neutrality target requires all kinds of effective technology measures. Hydrogen engines, fuel cells, batteries, and even others could all contribute to the portfolio approach to carbon neutrality. Single technology scenarios suggest potential delays in overall decarbonization and are also riskier.

However, the uptake of some technologies in a “mixed” scenario may compete and slow down others; success for hydrogen ICEs could mean delays or failure in the uptake of fuel cells, given a certain amount of investment available. FCEVs are ZEVs but hydrogen ICEVs are not ZEVs in the U.S. Will policies in favor of hydrogen ICEs undermine the effort of promoting FCEVs as a transportation electrification approach? There is no clear answer at this time.

Moreover, it is highly uncertain if market acceptance of hydrogen engines will reach a sufficient level to make a difference. By analogy, compressed natural gas (CNG) trucks running on biomethane are technologically mature, have great GHG reduction benefits (especially from a full fuel cycle perspective), and have a low upfront cost, but in reality CNG trucks have never gained significant market success in the U.S.

12. Industry actions for hydrogen engines

In November 2021, five automakers in Japan including Toyota jointly announced that they will take on the challenge of expanding fuel options through the use of ICEs to achieve carbon neutrality. Their common view is that the enemy is not ICEs and that the society needs diverse solutions toward carbon neutrality.

Lately, some vehicle manufacturers and suppliers have expressed interest in hydrogen engines, including but not limited to Cummins (manufacturer of engines and power generation products), Daimler (commercial vehicle manufacturer), Volvo (commercial vehicle manufacturer), Bosch (vehicle supplier), Mahle (parts maker), JCB (a British manufacturer of heavy-duty equipment for construction, agriculture, waste handling, and demolition), Westport Fuel Systems (supplier of advanced fuel delivery components and systems), DAF Trucks N.V. (commercial vehicle manufacturer in Europe), and Toyota (automobile manufacturer).

Hydrogen engines gain renewed momentum worldwide and the industry has been pushing for favorable policies; e.g., an EU regulatory change pending in 2023 would classify heavy-duty trucks using hydrogen engines as zero-emission vehicles (Automotive News, 2023), and the regulatory change was approved in 2024 (European Union, 2024).

13. Policies in the U.S. and the European Union

Recent policies in the U.S., including California, as well as in Europe, are relevant to the hydrogen ICEV vs. FCEV comparison, such as the regulatory treatment of these technologies and the impacts. These jurisdictions' policies are briefly reviewed below.

In April 2024, U.S. EPA released its approved phase 3 GHG emissions standards for heavy-duty vehicles, which include EPA's recognition of hydrogen ICEs in reducing CO_2 emissions (U.S. EPA, 2024a). ZEVs in the new standards still refer to technologies that result in zero tailpipe emissions, and example ZEV technologies include BEVs and FCEVs, which do not require costly testing and certification. Clearly, hydrogen ICEVs are not included in ZEVs, as they emit certain criteria pollutants and may also have negligible but nonzero CO_2 emissions at the tailpipe (U.S. EPA, 2024a). For manufactures to comply with engine CO_2 exhaust emission standards, EPA allows for not performing CO_2 emission testing for hydrogen ICEs if using an engine testing default CO_2 emission value (3 g/hp-hr), though manufacturers may instead conduct testing to demonstrate that the CO_2 emissions from their engine is below 3 g/hp-hr (U.S. EPA, 2024a). This leniency will likely reduce engine testing and certification burden for manufactures (U.S. EPA, 2024b). Note that NO_x and PM emission testing is required for hydrogen engines even fueled with neat hydrogen.

The performance-based standards do not require manufacturers to adopt any specific technologies (e.g., ZEV technologies); they can meet the standards through the use of a variety of technologies, with or without producing additional ZEVs or hydrogen ICEVs (U.S. EPA, 2024a). EPA's example potential compliance pathways include the hydrogen ICE technology only in the model year 2030 and later timeframe.

In California, the Advanced Clean Trucks (ACT) regulation requires medium- and heavy-duty manufacturers to produce and sell an increasing portion of their sales as ZEVs starting in the 2024 model year and ramping up through the end of the 2035 model year (CARB, 2019). Furthermore, the Advanced Clean Fleets (ACF) regulation requires fleets to phase in the use of ZEVs and manufacturers to reach

100% medium- and heavy-duty ZEV sales in California, beginning with the 2036 model year, and this policy applies to all Class 2b-8 vehicles (CARB, 2023b; CARB, 2023c). The ZEV definition is the same in the ACT and the ACF, as well as in the proposed 2024 ACT rule. A ZEV produces zero exhaust emission of any criteria pollutant (or precursor pollutant) or GHG under any possible operational modes or conditions (CARB, 2019; CARB, 2023b; CARB, 2024b). In contrast to the U.S. EPA policy approach, as of June 2024, California has not indicated that hydrogen ICEVs would be credited as being a ZEV, given the tailpipe emissions of pollutants. Unless this determination changes, hydrogen ICE trucks are not likely to be competitive in the state, as they will not be eligible for ZEV-related incentives; they also will eventually be banned, as per the 2036 phase-out target for ICE sales.

In May 2024, the EU ratified and strengthened the CO_2 emission standards for heavy-duty vehicles, while adjusting the flexibilities available to vehicle manufacturers for compliance (Mulholland, 2024). On the European market, a "zero-emission heavy-duty vehicle" could mean a heavy-duty motor vehicle without an ICE, or with an ICE that emits not more than 3 gCO_2/tkm for trucks or 1 gCO_2/pkm for buses and coaches (European Union, 2024; Mulholland, 2024). As an example, if hydrogen heavy-duty ICE trucks produce CO_2 emissions not more than the 3 gCO_2/tkm threshold, they can be classified as ZEVs. Therefore, zero-emission heavy-duty vehicles currently include BEVs, FCEVs, and other hydrogen-powered vehicles in Europe, and technological innovation continues (European Union, 2024).

14. Conclusions

The concept of hydrogen ICEVs has gained renewed interest lately, especially for heavy-duty trucks. This study has summarized a range of literature and relevant findings on hydrogen engines, as compared to hydrogen fuel cells, for trucking applications, including aspects such as vehicle efficiency, GHG and criteria pollutant emissions, hydrogen fuel purity, vehicle attributes, vehicle acquisition costs, TCOs, and new policies for hydrogen engines.

Below are a few key findings for hydrogen ICEVs when compared to FCEVs:

- Hydrogen ICEVs typically have lower overall efficiency and thus lower fuel economy, though in some situations (such as excavators which mostly operate at very high load) they may equal or outperform FCEVs;
- Hydrogen ICEVs may perform better than FCEVs (with better reliability and less performance decline) through the aging process;
- Hydrogen ICEVs are likely to have a purchase cost advantage, at least through 2030 or until FCEVs reach a large scale market and fuel cells achieve much lower cost of production;
- Due to their lower efficiency, hydrogen ICEVs may have a TCO disadvantage for on-road applications. They may also require greater hydrogen storage on board to have the same range as FCEVs;
- Hydrogen ICEVs can run with lower-purity hydrogen fuel, which could mean lower fuel prices and thus potentially decreased fuel costs, but the potential magnitude of this fuel price effect is unclear; and

- Hydrogen ICEVs emit significant NO_x emissions and therefore are not ZEVs in the U.S., which, in California and states adopting California's rules, could disqualify them under the ZEV mandates. In contrast, FCEVs are generally considered ZEVs internationally. Hydrogen ICEVs could achieve very low or near-zero NO_x levels with appropriate emission control systems; it is not clear if this could ever change their status in California, but this should make them be considered near-zero emission vehicles elsewhere.

In future work, additional data on actual in-use performance of hydrogen ICEVs vs. FCEVs will help to clarify some of the uncertainties reported here. Such data should become more available over the next few years if both types of truck are sold in significant numbers, which is just beginning to occur today.

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