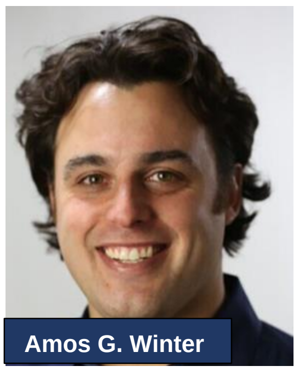
MIT Climate & Sustainability Consortium

Design of Onboard Hydrogen Storage for Heavy-Duty Vehicles

Project Overview

What is the most technically and economically promising zero-emission drivetrain for decarbonizing heavy-duty vehicles (HDVs)? How can we design a conformal hydrogen tank to provide a better storage solution for hydrogen HDVs?


Amos G. Winter

The transportation sector is the second largest contributor to CO_2 emissions, accounting for 27% of global emissions. While the light-duty vehicle market has been rapidly decarbonizing with the popularity of battery-electric drivetrains, heavy-duty vehicles (HDVs) remain challenging to decarbonize. Many socioeconomic and technoeconomic challenges exist, such as range anxiety, the lack of refueling infrastructure and the high refueling costs of alternative fuels, and the economic uncertainty of adoption among stakeholders.

To help address some of these challenges, the team at MIT's K. Lisa Yang Global Engineering and Research (GEAR) Center, led by Professor Amos G. Winter (Mechanical Engineering) and including Bryony DuPont and ZhiYi Liang, has been investigating different ways to decarbonize the heavy-duty transportation sector. In one of their recent efforts, by using class-8 trucks (heavy-duty trucks with a gross vehicle weight of at least 33,001 pounds) as a case study, they created a quantitative model to compare the technoeconomic tradeoffs between adopting battery-electric trucks versus hydrogen-fuel-cell trucks. The results of this work identified both technical limitations and the high economic costs of operating battery-electric class-8 trucks in long-haul applications, suggesting that biodiesel and hydrogen drivetrains are more competitive options. Supported by their technoeconomic analysis for hydrogen HDVs, the researchers have also been iterating the design of a conformal 700-bar hydrogen storage tank through both computational and experimental means, which will provide a more optimal solution to store hydrogen on HDVs.

This project aligns with MCSC's Transportation pathway.

Findings & Outcomes

The team analyzed the challenges that stakeholders currently face in decarbonizing diesel fleets, and quantified the technoeconomic tradeoffs between diesel, battery-electric, and hydrogen drivetrains from an operational perspective.

This MIT team has created a model that quantifies the technical limitations and the economic tradeoffs between traditional diesel drivetrains, battery-electric (BEV) drivetrains, and 700-bar hydrogen fuel-cell (FCEV) drivetrains.

They found that the energy density of the onboard energy storage system is a decisive factor in determining both the technical and economic viability of zero-emission freight vehicles, especially in long-haul applications. Hydrogen FCEV drivetrains are shown to be a more promising candidate than BEV drivetrains in decarbonizing conventional diesel drivetrains. Their results show that BEV class-8 trucks are intractable for long-haul applications above the 500-mile range, due to the low energy density of lithium batteries and the weight limitation onboard. For example, class-8 trucks with a 500-mile range will lose approximately half of their cargo capacity for battery allocation, making the levelized cost of shipment in using BEVs for long-haul inherently expensive and economically unattractive (Fig 1).

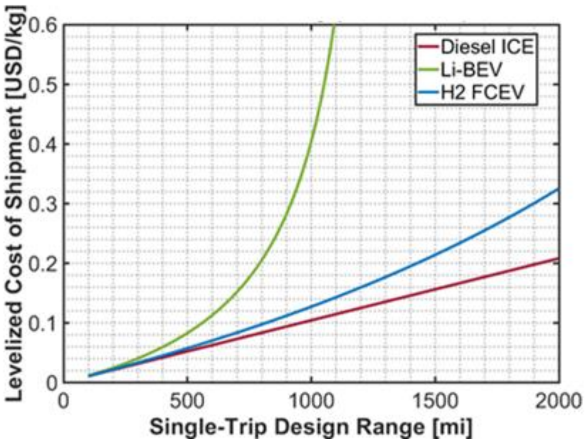


Fig 1 The levelized cost of shipment increase exponentially with battery-electric drivetrain, with hydrogen being more promising contender to replace diesel.

As a low-weight fuel, hydrogen is a promising replacement fuel for use in FCEVs. However, hydrogen has low volumetric energy density and is a gas at room temperature, requiring it to be pressurized up to 700-bar to be used onboard a FCEV. The pressure vessels required to store 700-bar hydrogen add significant weight, lowering an FCEV's overall energy storage density. With the combined weight of the hydrogen tanks, storing 700-bar hydrogen remains less energy dense compared to storing liquid diesel. This leads to a slight reduction in cargo capacity and added levelized cost of shipment (Fig 1) in FCEV long-haul trucks compared to existing diesel fleet.

In addition, hydrogen fuels have yet to reach price parity with diesel fuel, making the transition from traditional diesel fleets towards FCEVs economically challenging. Based on the team's technoeconomic projection, a class-8 hydrogen FCEV truck remains more expensive to operate than a conventional diesel truck, but still more profitable than operating a BEV truck. Currently, industry stakeholders do not have an economic incentive to phase out their diesel trucks and make the switch to hydrogen trucks, due to the high cost of hydrogen and lack of hydrogen infrastructure.

From these results, the team concluded that more supportive government incentives favoring hydrogen HDVs will be necessary to encourage the adoption of hydrogen fleets and the expansion of capital investments toward hydrogen supply infrastructure to create a smooth transition away from conventional diesel fleets. Simultaneously, a strong fiscal pressure to shrink the existing diesel fleet (e.g., a carbon tax) will also be favorable in reducing tail pipe emissions and decarbonizing the heavy-duty transportation industry.

Publications

These findings were presented at the ASME 2024 IDETC-CIE conference and published in a conference proceeding titled "*Techno-economic Outlooks for the Operation of Zero-Emission Heavy-Duty Trucks: Their Implications on Fleet Operators, Cargo Shippers, and Vehicle Designers*."

Building on this operational analysis, the team is designing a conformal hydrogen storage architecture that has higher and packing density, easier manufacturability, and is more cost effective for heavy-duty hydrogen vehicles.

By working with industry stakeholders, the team has identified significant drawbacks to the typical hydrogen tank design (Fig 2), which could be inhibiting the adoption of hydrogen heavy-duty vehicles (HDVs). The current design used to store 700-bar hydrogen has a bulky cylindrical shape with metal-reinforced hemispherical domes. This bulky nature of the large diameter tanks makes integration difficult inside a highly space-constrained vehicle chassis (base frame) that tends to have an irregular shape. To incorporate storage tanks into current hydrogen vehicles, automotive manufacturers must often make compromises in the vehicle design, such as removing the sleeper compartment in the truck's tractor, making them intractable for long-haul truck drivers.

Fig 2 Current COPV design to store 700-bar hydrogen.

The researchers propose a hydrogen storage solution that leverages commoditized carbon fiber tubes to create an onboard 700-bar hydrogen storage system that is conformal to irregular chassis geometry (Fig 3). Preliminary simulations project that the new design would have a higher energy packing density and easier manufacturability than the current composite overwrapped pressure vessels (COPV) design, enabling longer vehicle range at potentially cheaper cost. They created an engineering design framework to model the fundamental mechanics that govern the strength performance of the vessel and have created a parametric design framework to make the design feasible.

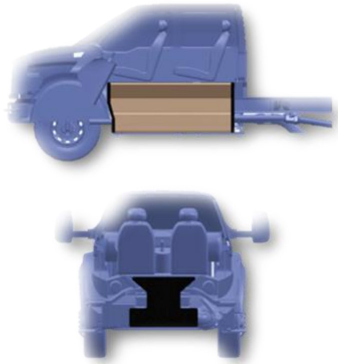


Fig 3 Conformal 700-bar hydrogen storage solution proposed by Winter's team.

Over the past year, two potentially feasible hardware designs have undergone bench-top level experimentation to evaluate physical strength performance and are currently being further iterated.

Opportunities for Implementation

- The commercialization and integration of GEAR Center's conformal storage tank will allow hydrogen heavy-duty trucks to have a more optimal design for long-haul applications, allowing them to be more readily adoptable by industry stakeholders to replace existing diesel fleet
    - Truck manufacturers can fit hydrogen storage into irregular space within vehicle chassis (e.g. between ladder frames)
        - Minimizing design modifications on existing mass-produced vehicle frame structures and OEM no longer need to redesign chassis around storage tanks
        - Restoring the sleep-in-truck utility of a long-haul vehicle by eliminating the need to reallocate the sleeper compartment for storage tanks, and making hydrogen trucks more desirable to drivers for long-distance applications
    - The team's conformal storage tanks are lighter and more compact than existing filament-wound hemispherical tanks, enabling a more efficient way to store hydrogen onboard and a longer driving range
    - This conformal storage design is modular and can be manufactured using commoditized carbon fiber tubes. It allows a tank manufacturer to reduce manufacturing costs and complexity compared to the current individually-filament-wound tank
- The team would like to work with industry partners on the following:
    - Discuss with fleet operating companies to further elucidate the user-driven needs of hydrogen vehicles in heavy-duty and long-haul applications, especially from an operating range and power consumption perspective. This will help the researchers to better understand the secondary function requirements from the operating standpoints and optimize the conformal hydrogen storage design for those application-specific needs
    - Partnering with fuel-tank manufacturers and vehicle manufacturers to:
        - Quantify manufacturing constraints and vehicle-specific technical requirements to refine the team's existing conformal storage design
        - Manufacture scale-up prototypes and conduct experimental pilot study to test the technology real-world operating conditions
        - Optimize the design towards cost-reduction and mass-manufacturability, pathing the road towards regulatory certification and commercialization of the technology
- This study also helped elucidate the value chain – vehicle manufacturers, shipping fleet operators, and cargo shippers – that should be considered when decarbonizing diesel fleets.
    - The current cost of renewable hydrogen has yet reach price parity with diesel fuel, indicating the needs for more aggressive government policy and economic incentives supporting hydrogen infrastructure and fuel-cell vehicles.