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Analysis of Hydrogen Fuel Cell Class 8 Trucks

Today, one of the most important challenges scientists face is decarbonizing the global economy. While alternative forms of energy such as solar and wind have prevailed in the electricity generation sector, the transportation sector, which mainly relies on petroleum, is still figuring out ways to decarbonize. A promising method is using hydrogen fuel cell vehicles (FCEVs).

FCEVs convert hydrogen into electricity, which powers their electric drive train. Hydrogen fuel cells produce zero CO_2 emissions, only admitting water as a byproduct through an oxidation reduction reaction. Fuel cell technologies have the potential to allow for higher energy storage density than conventional fuels, faster refueling and recharging rates, and longer driving ranges.[1]

This paper specifically focuses on hydrogen fuel cell class 8 trucks. Class 8 trucks are vehicles that weigh over 53,000 lbs., which are most commonly 18-wheeler trucks. Heavy duty vehicles contribute to 23% of transportation emissions of greenhouse gases and a quarter the fuel consumed annually due to long traveling distances and heavy cargo.[2] Therefore, sizable reduction of transportation sector emissions could be accomplished by using alternative fuels, such as hydrogen, for trucks.

While FCEVs reduce carbon emissions, currently, a challenge surrounding FCEVs and class 8 hydrogen trucks is the cost of compressing hydrogen. As pressure increases, the compression cost as well as capital costs of compressors, storage, and refrigeration increase. Today, hydrogen is compressed at either 350 or 700 bar. While 350 bar would be the cheaper option, less hydrogen fuel is stored at 350 bar, and therefore, reduces the total range of the vehicle. Since cost is related to hydrogen pressure, there may be opportunities to reduce cost by lowering the pressure at which fueling stations dispense hydrogen.

This paper examines the relationship between hydrogen pressure, driving range, and hydrogen price for Class 8 vehicles. By doing so, optimal pressure storage can be concluded for a given driving range to minimize cost. This analysis shows, for example, that dispensing hydrogen at 350 bar instead of 700 bar reduces a truck's fuel costs by $0.10-0.13/mile while reducing drive range by 190-250 miles (a 34% reduction).

Estimating miles/kg H_2 and fuel tank volume

To understand the relationship between pressure and driving range, first the amount of hydrogen stored vs. mileage was analyzed. The more onboard hydrogen stored, the farther the 18-wheeler truck would be able to drive. Using data from the academic literature, Figure 1 was computed at a fixed pressure of 350 bar. [3]

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[1] Data From https://www.hydrogen.energy.gov/pdfs/19006_hydrogen_class8_long_haul_truck_targets.pdf
[2] Data from https://www.ornl.gov/news/heavy-duty-vehicles-ideal-entry-hydrogen-fuel-cell-use
[3] Data from https://www-sciencedirect-com.ezproxy.lib.utexas.edu/science/article/pii/S0739885916301639, https://www-sciencedirect-com.ezproxy.lib.utexas.edu/science/article/pii/S036031991633676X

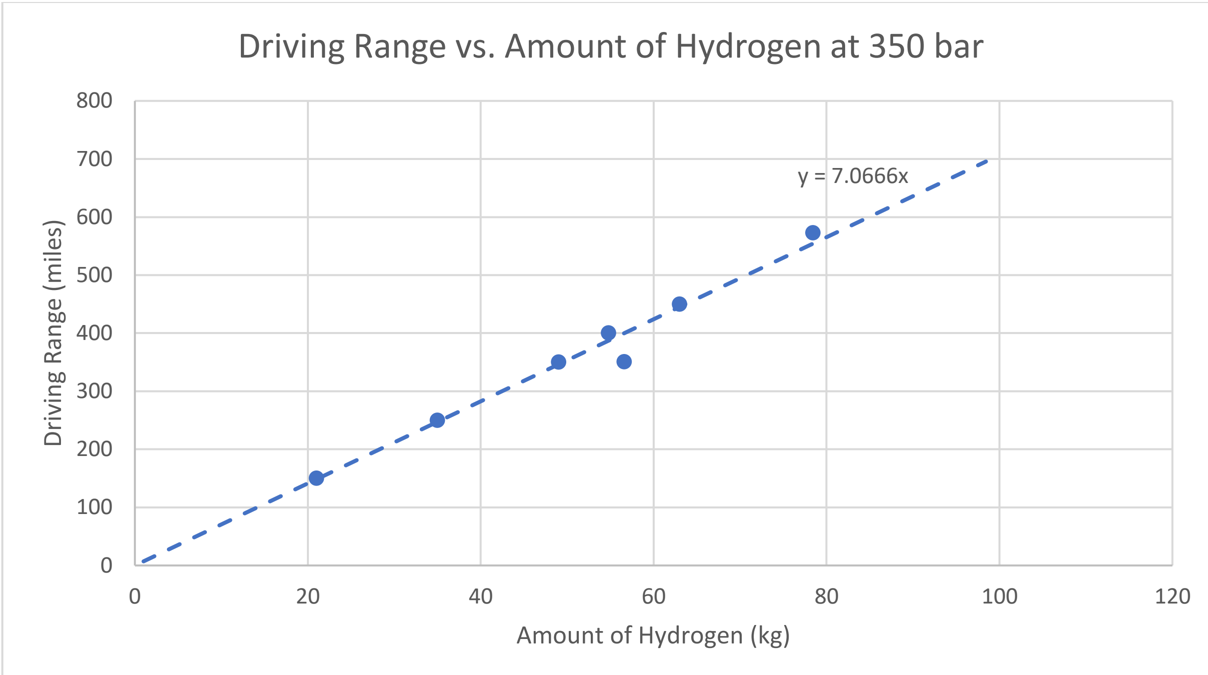

Figure 1: Driving Range vs. Amount of Hydrogen Stored on Class 8 Vehicles at 350 bar.

The linear model gives an average of about 7 miles/kg H_2, which is a lower estimate than the Department of Energy's data of 9.4 miles/kg H_2.[4] A hydrogen calculator tool was used for several calculations. Further discussion of this device is provided in the appendix. Using the equation from the hydrogen calculator, density was calculated using the equation below, where Z=1.222 and 1000 is used as a conversion factor to get density in units of kg/m^3. Assuming 273 K, the density of hydrogen at 350 bar is 25.02735 kg/m^3.

$$\rho = \frac{MW \times P}{ZRT(1000)} \quad (1)$$

Since volume = mass/density, using a 54.8 kg of hydrogen, which provides approximately 400 miles, thee volume of the tank for a middle amount of hydrogen storage was found to be 2189.6 L. Therefore, an assumption of a 2000L storage tank onboard a Class 8 vehicle is assumed for the following sections.

Density and Mileage vs. Pressure

Since hydrogen is not an ideal gas, the relationship between density and pressure cannot be assumed as linear. Using the hydrogen calculator, which utilized equation 1 above, densities were calculated at different pressures at a constant temperature of 273K, outputting Figure 2.

[4] Data from https://www.hydrogen.energy.gov/pdfs/19006_hydrogen_class8_long_haul_truck_targets.pdf

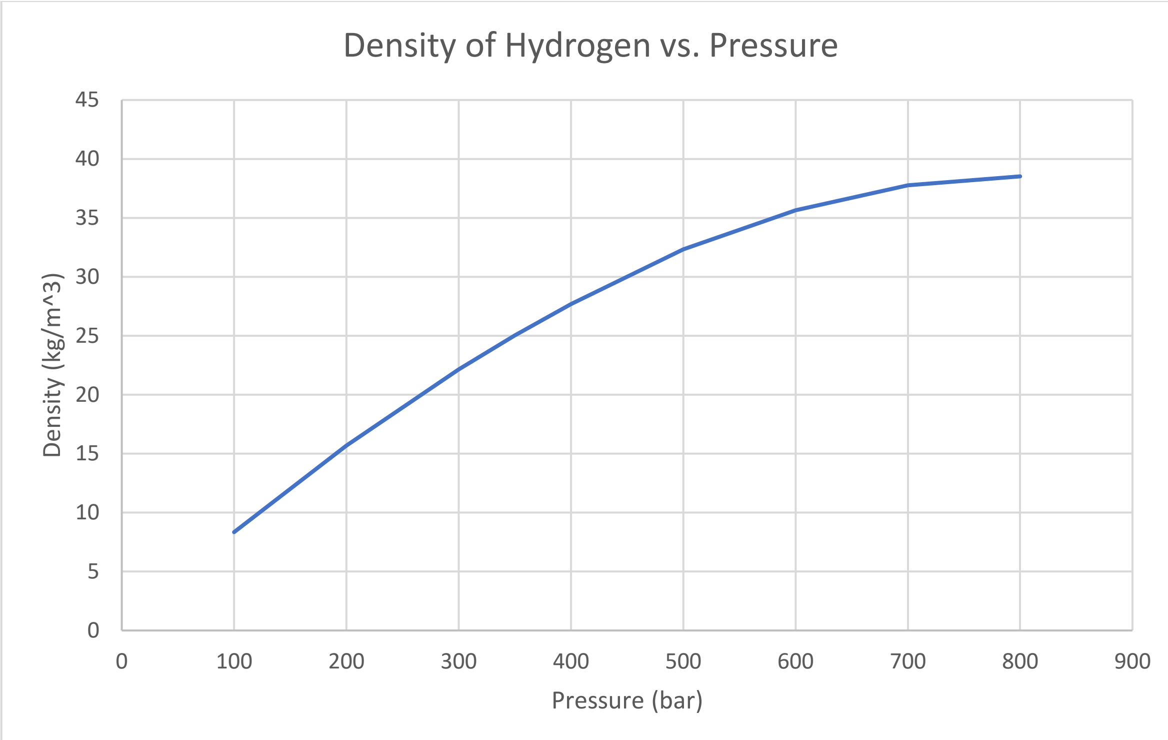

Figure 2: Density vs. Pressure of Hydrogen at 273K.

Figure 2 confirmed the nonlinear relationship between the two parameters. At higher pressures, bigger pressure changes do not have as big of an effect on the changes of density. This is because at low pressures, gases are highly compressible, meaning that density changes are more significant. However, as higher pressures are encountered, the molecules are packed closer together and start to approach liquid behavior. Therefore, the gas becomes less compressible, resulting in less significant changes in density. This nonlinear relationship between density and pressure prove that the amount of hydrogen stored at different pressures are also not linear. Thus, driving range vs. pressure is not expected to follow a linear relationship. A 2000 L tank is assumed to be an appropriate size for storing a given amount of hydrogen for 18-wheeler trucks. The amount of hydrogen stored at different pressures was calculated using the H2 calculator. Then, equation 2 was used to calculate the average miles that can be driven at different storage pressures.

$$miles = 7.0666 \frac{miles}{kg\ H_2} \times kg\ H_2 \quad (2)$$

Additionally, the higher DOE fuel economy of 9.4 miles/kg H_2 was plotted at different temperatures.

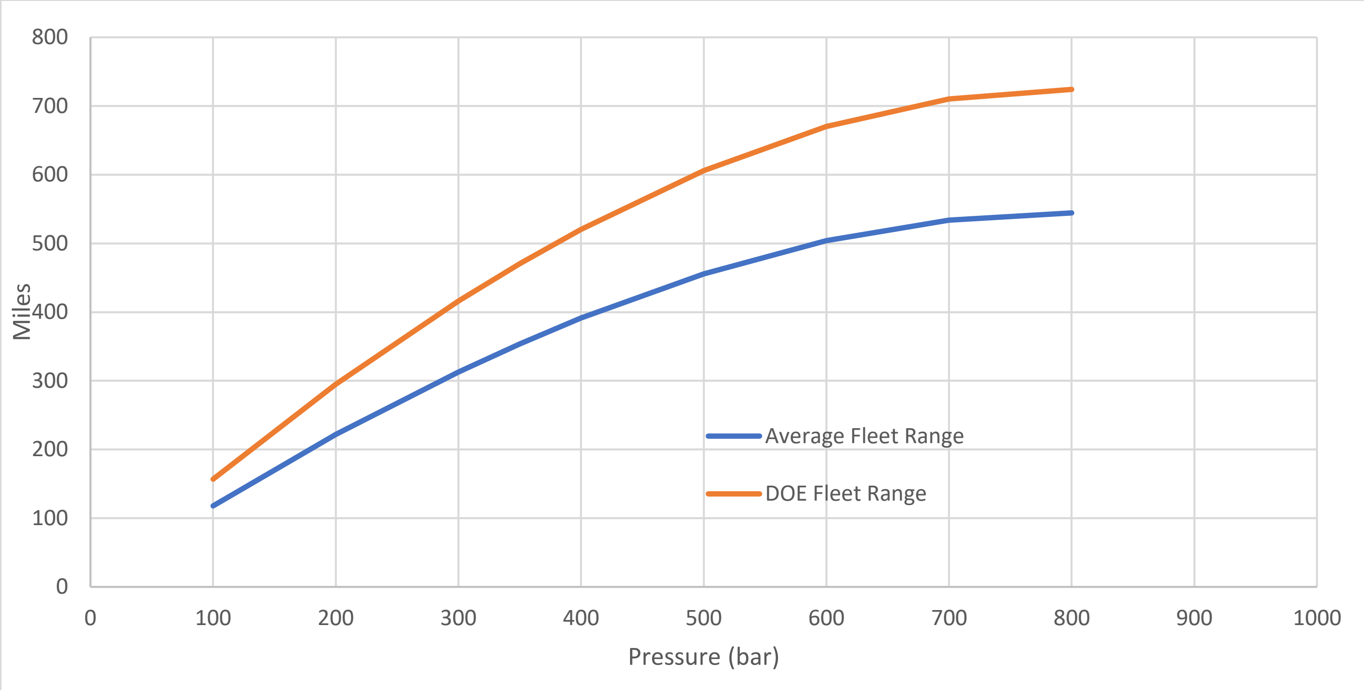

Figure 3: Mileage vs. Pressure at a Constant fuel tank Volume of 2,000 L.

Initially, an increased pressure provides extra mileage. However, as higher pressures are reached, there is less of an advantage. To utilize this conclusion, compression energy and capital costs must be calculated to determine the tradeoff between pressure, mileage, and cost.

Compression Energy and Cost

To estimate the impact of pressure on hydrogen cost, first compression energy at different pressures must be calculated using equation 3, which assumes adiabatic compression.[5]

$$W = \frac{\gamma}{\gamma - 1} P_0 V_0 \left(\left(\frac{P_1}{P_0} \right)^{\frac{\gamma - 1}{\gamma}} - 1 \right) \quad (3)$$

$$W = [\frac{J}{kg}]$$

$$P_1 = [Pa]$$

$$P_0 = [Pa] = 101324 \; at \; atmospheric \; conditions$$

$$V_0 = [m^3/kg] = 11.11 \frac{m^3}{kg} at \; atmospheric \; conditions$$

$$\gamma = 1.41 \; for \; H_2$$

Using equation 3, work was outputted at different pressures and converted from J/kg to kwh/kg. The relationship of compression energy was concluded to be a power function as it outputs a

[5] Data from https://afdc.energy.gov/files/pdfs/hyd_economy_bossel_eliasson.pdf

term that is a product of a coefficient and has the variable (P_1) raised to a constant. The assumption of adiabatic compression is valid for compression energy analysis, but in reality, a system will never be perfectly adiabatic as some heat will always be lost. More generally, gas compression is typically done in multiple stages and cooled after each state, suggesting a more isothermal rather than adiabatic thermodynamic conditions.

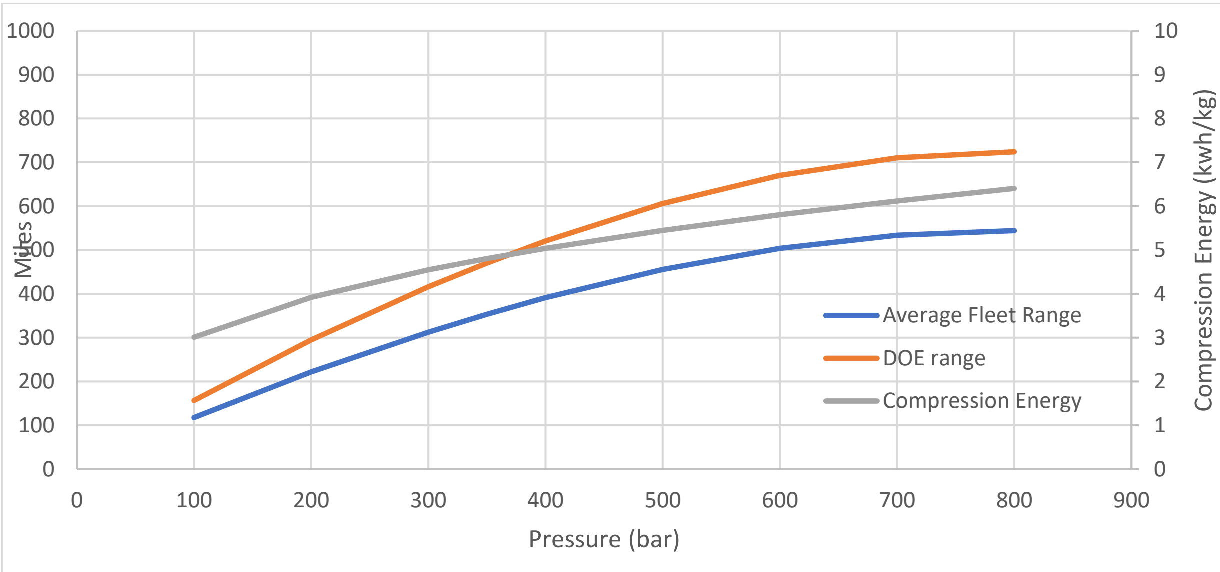

Figure 4: Compression Energy vs. Pressure at a Constant fuel tank Volume of 2,000 L.

To output compression costs, the grid electricity for hydrogen was assumed to be 7.98 cents/kWh or 0.0798 $/kWh.[6] The compression energy was then multiplied by the electricity grid costs to output Figure 5.

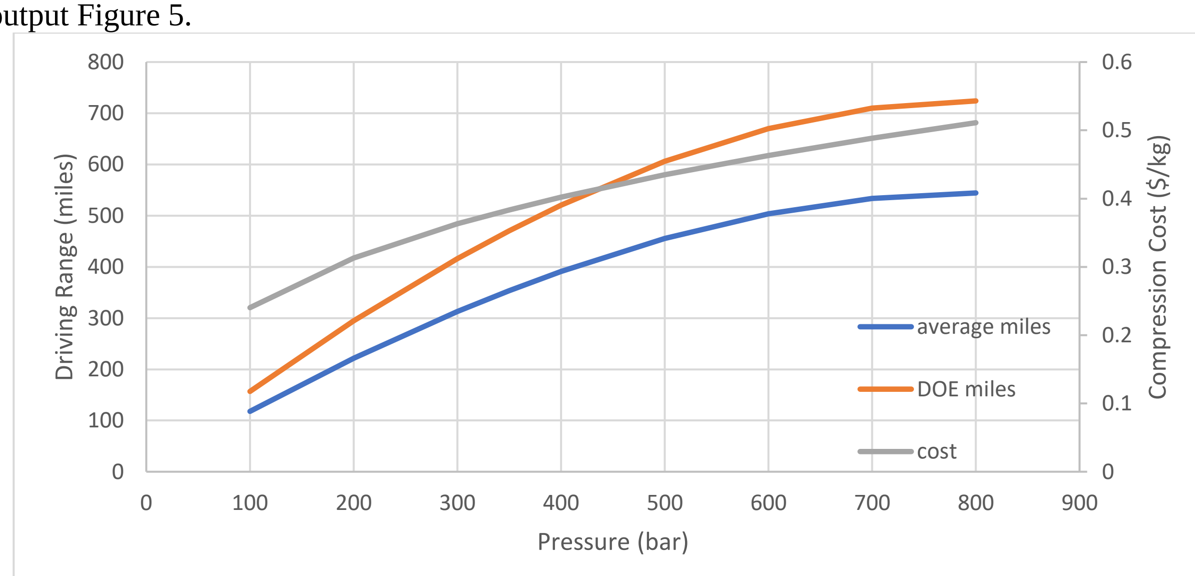

Figure 5: Compression Cost vs. Pressure at Constant Volume

[6] Data from "Texas State Energy Profile (2020), U.S. Energy Information Administration. Accessed online via < https://www.eia.gov/state/print.php?sid=TX>"

The relationship between compression cost ($/kg) and pressure was assumed to follow the same relationship density vs. pressure as different amounts of hydrogen are stored at a given pressure. Figure 4 shows that at a higher pressure, it will cost more to compress hydrogen. However, at higher pressures, the cost becomes less significant as the gas becomes less compressible.

Capital Cost vs. Pressure

Capital costs of the compressor, storage, and refrigeration were found using the HDSAM model from the DOE.

Table 1: Capital Costs for 350 and 700 bar.[7]

	350 bar			700 bar		
	Compressor	**Storage**	**Refrigeration**	**Compressor**	**Storage**	**Refrigeration**
Capital Cost [$/kg]	0.31	0.12	0.16	0.67	0.29	0.35
Other Cost [$/kg]	0.14	0.04	0.06	0.26	0.04	0.07

The total capital and other costs were found to be $0.83/kg and $1.68/kg for 350 and 700 bar respectively. Since the capital costs were found to double between 350 and 700 bar, the relationship between capital costs and pressure was assumed to be approximately linear over this range. At higher pressures, the greater the capital costs are higher due to a need for more compression, better storage, and more refrigeration to keep the gas cool when compressing at higher pressures. To complete a full analysis of costs, the capital costs were added with the compression costs to yield $1.22/kg for 350 bar and $2.17/kg for 700 bar.

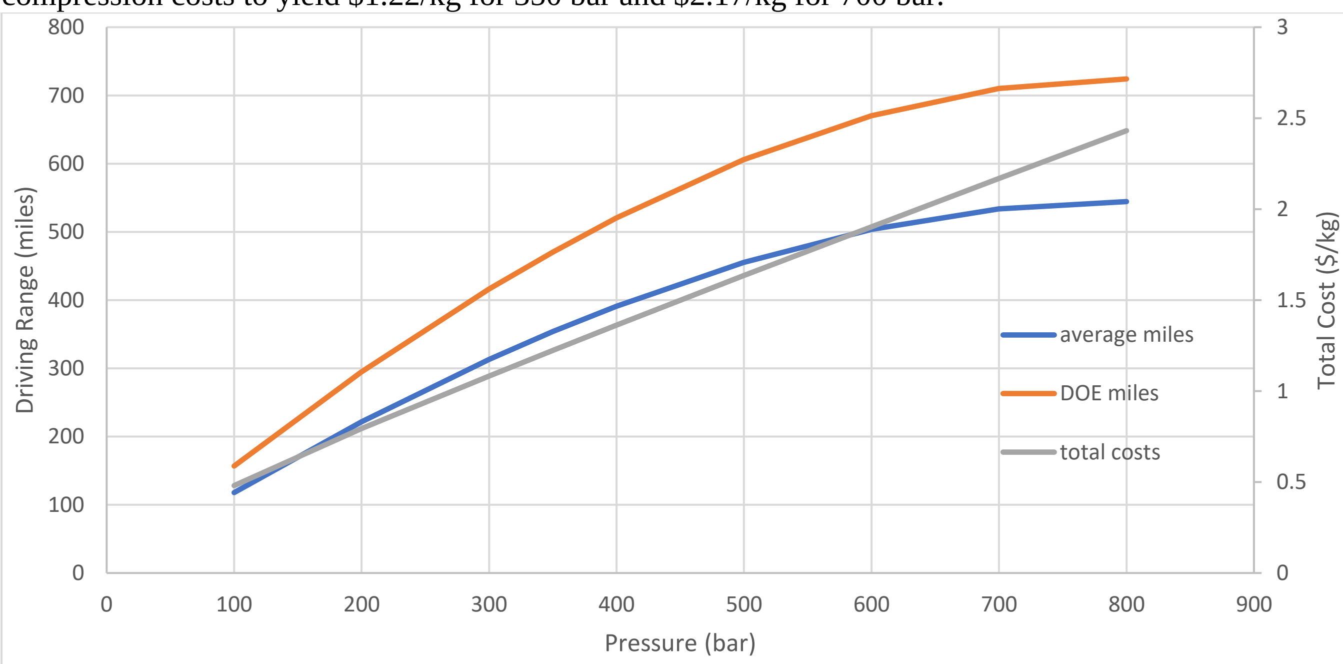

Figure 6: Total Costs vs. Pressure.

[7] Data from HDSAM DOE Model

$/Mile vs. Pressure

To show the tradeoff between driving range and pressure, $/mile was computed by dividing the total cost in Figure 6 by fuel efficiency, which was found to be 7.0666 miles/kg from Figure 1 or 9.4 miles/kg by the DOE standard.

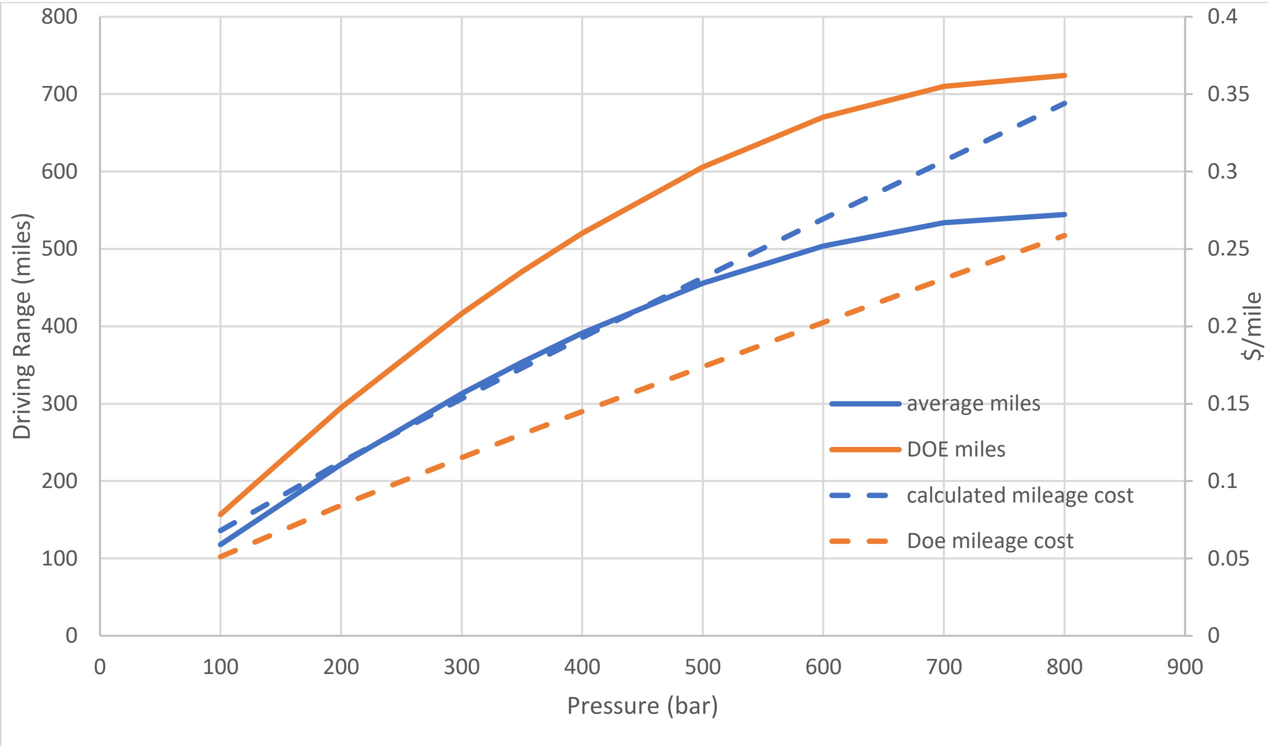

Figure 7: $/mile vs. Pressure.

For 350 bar, the cost per mile was $0.17/mile using the calculated fuel efficiency or $0.13/mile using the DOE fuel efficiency. Similarly, for 750 bar, the values were $0.31/mile and $0.23/mile. If the hydrogen fuel cell system was operating at 350 bar, the operator would save between $0.10/mile to $0.13/mile depending on the fuel efficiency of the truck. Based on Figure 3, operating at 350 bar would reduce the driving range between 190 and 250 miles (a 34% reduction in drive range) depending on the fuel efficiency of the truck.

Conclusions

Currently, the cost of 700 bar hydrogen at the fueling station ranges from $6-8/kg or $0.64-0.85/mile.[8] Compared to diesel, which is about $0.43/mile, hydrogen is still too expensive to compete economically. However, by reducing the pressure to 350 bar, we estimate that the hydrogen prices could drop to $0.54-0.75/mile, which is closer to being competitive with diesel. Thus, the operating pressure of the hydrogen fuel cell system plays a role in helping to lower the cost and providing an economical alternative to diesel.

[8] Data from https://www.osti.gov/pages/servlets/purl/1393842#:~:text=The%20current%20hydrogen%20refueling%20station,stations%20supplied%20with%20liquid%20hydrogen.

However, operating at 350 bar also reduces driving range, which limits its application. Operating at 350 bar yields savings of $0.10/mile to $0.13/mile while reducing the range 190-250 miles as opposed to 750 bar. At 350 bar, 350-470 miles can be achieved. A typical class 8 vehicle travels 600-650 miles a day. Therefore, for many class 8 freight routes, 350 bar pressure may not provide enough driving range.

However, there may be many routes where a range of 350-470 miles would be appropriate—for example, regional distribution routes—and the savings from using lower hydrogen pressure may impact the truck's ability to operate with hydrogen fuel profitably. Alternatively, trucks needing 600 miles of drive range would yield some savings by using 600 bar, which provides 500-670 miles of driving range. The flexibility to buy hydrogen at a pressure that suits a truck's drive range needs may provide costs reductions that make hydrogen more attractive as an alternative transportation fuel.

Next Steps

To show the potential of FCEVs more generally, other classes of vehicles should be explored, such as regional haul, medium duty trucks, and transit buses. Analyzing different vehicles in terms of pressure and driving range allows for a better understanding if hydrogen fuel cells provide a better option for these classes of vehicles, which typically have shorter ranges.

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Disclaimer and Acknowledgement

This preliminary report, not peer reviewed, based on information developed during a more comprehensive investigation, which is intended to be published as a peer reviewed document. Comments and suggestions for improvements are welcome and should be sent to the technical leader of this task, Dr. Thomas Deetjen, t.deetjen@cem.utexas.edu.

While UT researchers are solely responsible for the information presented, they want to thank the industrial and government participants in the H2@Scale DOE-funded project in which UT is privileged to participate for helping the UT researchers better understand the opportunity and constraints.

Appendix

Table 1: Data input for Figure 1at 350 bar[9]

Amount of Hydrogen (kg)	Driving Range (miles)
56.6	350.92
54.8	399.9852
78.43	572.93115
21	150
35	250
49	350
63	450

H2 Calculator Information[10]

The H2 Calculator calculates density and therefore mass at different pressures, temperatures, and volumes. Equations 4 and 5 below were used to calculated density (kg/m^3) and mass (kg) respectively, where R=8.31477 kJ/kmolK, MW=2.01588 kg/kmol, Z is known for different parameters, and 1000 is used as a conversion factor.

$$\rho = \frac{MW \times P}{ZRT(1000)} \qquad (4)$$

$$mass = \frac{\rho V}{(1000)} \qquad (5)$$

[9] Data from https://www-sciencedirect-com.ezproxy.lib.utexas.edu/science/article/pii/S036031991633676X and https://www-sciencedirect-com.ezproxy.lib.utexas.edu/science/article/pii/S0739885916301639
[10] Data from Eric W. Lemmon et al, Standardized Equation for Hydrogen Gas Densities for Fuel Consumption Applications, 06CONG-22