Optimizing Hydrogen Storage for Military Vehicle Applications

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Abstract

As the Army begins to explore the electrification of its ground vehicle fleet, several technologies are of interest to help clear the large hurdle presented by vehicles' energy needs. Hydrogen fuel cells have potential as a solution to this problem but there are many challenges that need to be addressed, such as hydrogen storage. Siemens LMS Amesim was used to simulate the performance of several wheeled and tracked vehicles in order to evaluate several hydrogen storage methods and materials to determine if they are suitable for military ground vehicle use. Several technologies were found to perform better than the state of the art compressed gas storage, exemplifying that advanced hydrogen storage could enable the electrification of the heaviest ground vehicles in the Army's fleet.

Keywords

Hydrogen; hydrogen storage; fuel cells; fuel processing and storage; modeling and simulation

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Introduction

The Army has identified climate change as a significant threat, increasing the difficulty of the Army's core mission. In order to face the threat posed by climate change, the Army has planned several lines of effort including the fielding of fully electric tactical vehicles by 2050 [1]. A technology of interest that has the potential to mitigate these issues while maintaining vehicle performance is hydrogen fuel cells. However, hydrogen is not without its difficulties, namely poor volumetric energy density at ambient conditions. Many hydrogen storage methods have been studied over the past decade, but there has not been an in-depth study on how certain methods would fit into military vehicle applications.

Hydrogen is of military interest due to the quieter and cooler operation compared to internal combustion engines. Proton exchange membrane (PEM) fuel cells, a common fuel cell type used in automotive applications, operate at around 80°C [2]. This is a significantly lower temperature than diesel engines typically used in military vehicles, reducing the thermal signature immensely. PEM fuel cells also operate very quietly due to a lack of moving parts. Advantageous as it may be, hydrogen is not without flaws. In the gas phase, it has a very poor energy density. Storing hydrogen as a compressed gas requires lightweight but difficult to package cylindrical pressure vessels usually constructed from expensive carbon fiber. There are several technologies that have been developed to store hydrogen in a more effective way. Most of these have been investigated in passenger vehicle applications, not heavy-duty applications that would be more relevant to military vehicles.

Scope

A select group of vehicles and hydrogen storage methods and materials were investigated for this analysis. The vehicles included are the M1280 Joint Light Tactical Vehicle (JLTV), M1085 Long Wheelbase Medium Tactical Vehicle (LWB MTV), M1075 Palletized Load System (PLS), M113 armored personnel carrier, Mobile Protected Firepower prototype (MPF), and M88 Recovery Vehicle. These vehicles were selected for a variety of weight ranges for both wheeled and tracked vehicles. The weights range from the 10,000 kg class to above 50,000 kg in roughly 10,000 kg steps to provide a broad range of data.

The hydrogen storage methods and materials included in this analysis are 350 and 700 bar compressed gaseous hydrogen, liquid hydrogen, cryo-compressed hydrogen (CcH_2), aluminum hydride (alane), magnesium nanoparticles encapsulated in reduced graphene oxide (rGO-Mg), metal organic framework 5 (MOF 5), and methylcyclohexane (MCH)/toluene liquid organic hydrogen carrier (LOHC).

A fuel cell hybridized with a battery is used as a "drop in" replacement for the engine. A simple hybrid control strategy is used to control if the power comes from the fuel cell or the battery. For each simulation, the strategy was set to sustain the charge of the battery to maximize the usage of the fuel cell, also known as charge sustaining. Regenerative braking was also simulated to recapture some of the vehicle's energy while braking.

Assumptions and Methodology

The vehicle model was made using Siemens LMS Amesim. The core of the model was the road load equation. For each vehicle, a one-dimensional model was built that accounted for the speed, grade, rolling resistance, cooling load, drag, and fuel consumption. For ease of analysis, vehicles are assumed to be weight neutral after the conversion to a fuel cell powertrain. The model includes performance characteristics for an 80 kW fuel cell stack, which is scaled in integer steps depending on vehicle power requirements, as some vehicles require more than 80 kW. The polarization and fuel consumption curves are used to calculate the amount of hydrogen consumed at any point in time. This fuel consumption is output and compared to the hydrogen storage material properties.

The material properties of the hydrogen storage technologies of interest were compiled from literature sources and physical property databases. Fluid flow and heat transfer models were used to calculate the flow rate and thermal loading requirements for the gaseous and cryogenic storage systems. Both heat transfer and kinetic models were used to determine the reaction rate and heater energy needed for the material-based hydrogen storage technologies.

Results and Discussion

Vehicle parameters including weight, frontal area, drag coefficient, and rolling resistance were input into the Amesim model. The first simulation was run to determine how much hydrogen is required onboard each vehicle to meet the required range in Table 1. Vehicle speed was set to a constant value, described in Table 1, on a 0% grade paved road 10 miles long.

Vehicle	**Speed (mph)**	**Economy (mi/kg)**	**Required Range (mi)**	**Required H_2 Storage (kg)**
M1280	35	23.2	300	12.9
M1085	35	10.6	300	28.4
M1075	35	6.7	300	44.7
M113	25	3.8	300	78
MPF	25	3.3	300	91
M88	20	0.88	280	318.9

Table 1: Hydrogen storage capacity simulation results.

As expected, the amount of hydrogen required onboard increases with vehicle weight. Lighter vehicles achieve better fuel economy and utilize less power, requiring less fuel to meet the range target. There is also a noticeable increase in power and fuel needs for tracked vehicles compared to wheeled vehicles. This could be due to the varying frontal area, as the tracked vehicles have a much more box-like profile than the wheeled vehicles, and the increased rolling resistance of the track. The required amount of hydrogen stored on board the vehicle is used in later calculations to determine several storage system parameters, such as overall mass, volume, and heater power requirements.

In addition to the flat 10 mile simulation, two courses were simulated: Munson, a primary road with a single hill, and Churchville, and aggressive cross country course. The profiles are based on courses at Army Testing and Evaluation Command (ATEC). These courses were simulated to find the maximum hydrogen consumption rate at the fuel cell, which is a metric that is used to determine if a storage technology is appropriate for use in the vehicles modeled.

Hydrogen consumption over the courses followed the same trend seen in the flat simulation with the heavier vehicles exhibiting higher peak hydrogen consumption than the lighter vehicles. The highest peak hydrogen demand for all vehicles was seen on the off road course. Consumption ranged from 1.4 grams per second (g/s) for the M1280 to 11.8 g/s for the M88.

Based on the results of the first simulation, the mass of each system for each vehicle was calculated. The required amount of hydrogen was divided by the gravimetric capacity of the system to provide the overall system mass, shown in Table 2.

There are several interesting trends to note. The first is that the heaviest storage technology is 700 bar compressed gas. Even with material advances, the sheer amount of carbon fiber required to safely store such high pressure hydrogen is still significant. High safety margins are required and long service life is expected, driving the need for bulky systems. A potential compromise is 350 bar compressed hydrogen, which requires less material due to the lower pressure. However, the loss of capacity due to the lower pressure while remaining the second heaviest system make its use difficult to justify.

Method	**M1280**	**M1085**	**M1075**	**M113**	**MPF**	**M88**
350 bar	239	526	828	1444	1685	5906
700 bar	307	676	1064	1857	2167	7593
Liquid	163	359	566	987	1152	4037
CcH2	117	258	406	709	827	2899
rGO-Mg	198	437	688	1200	1400	4906
Alane	128	281	443	772	901	3157
MOF-5	165	364	573	1000	1167	4088
MCH	208	458	721	1258	1468	5144

Table 2: The mass of the hydrogen storage system for each vehicle in kilograms.

On the other hand, cryo-compressed hydrogen (CcH_2) is consistently the lightest weight storage method. CcH_2 involves the storage of hydrogen at cryogenic temperatures and elevated pressures, usually around 60 K or below and 500 bar [3]. Storing the hydrogen at elevated pressures significantly reduces the boil-off of hydrogen compared to liquid [4]. Boil-off is the release of hydrogen from the ullage (gaseous layer above the liquid) to maintain operating pressure in the vessel as hydrogen boils due to external heat input. Storing the hydrogen in a compressed state at cryogenic temperatures reduces the frequency of hydrogen gas purges because the system is designed to handle pressure. This is not the case with conventional liquid storage, which is designed to hold an unpressurized cryogenic liquid. The increased density of hydrogen in its liquid state allows for significantly more to be stored onboard while the low pressure operation requires less material than compressed gas. There is a requirement for insulation and heat exchangers, which slightly increase the weight compared to CcH_2. There is one significant drawback with liquid hydrogen storage: boil-off. If a vehicle sits dormant for an extended period, the potential exists to lose a significant amount of hydrogen to boil-off, reducing the ability for vehicles to be ready for use at a moment's notice. The release of hydrogen from vehicles also introduces a challenge in storing the vehicles when not in use. The vehicles will need to be stored in a well-ventilated area that will not allow for the accumulation of hydrogen due to the wide flammability range of the gas [5].

Another concern that is applicable to both liquid and CcH2 is the energy cost of liquefaction. Hydrogen has a very low boiling point of 22 K, requiring significant energy to reach. About 40% of the higher heating value of hydrogen is required to liquefy hydrogen with current technologies [6]. This energy cost is not borne by the vehicle but rather an external cost paid at the or before the fueling point, so there is no impact in range due to this energy requirement. This is a significant area for improvement and there are some technologies being developed to reduce the energy input for hydrogen liquefaction, such as magnetocaloric liquefaction [7].

Of the less conventional hydrogen storage materials, alane has the lowest weight followed by MOF-5. Both are slightly heavier than CcH_2, yet significantly lighter than both compressed gas systems. This is encouraging, as alane is a stable hydrogen storage medium that can allow for long-term storage of vehicles. The drawback for alane is that it is a single use material, much like a primary battery. The hydrogen can be easily released from the material onboard a vehicle by heating, but it cannot be easily recharged onboard a vehicle due to thermodynamic constraints [9]. In order to refill the vehicles with alane, solid block(s) will need to be unloaded and reloaded, which could become a time consuming process. Depending on the vehicle, significant amounts of alane are required, ranging from 100 kg to over 1,500 kg. Smaller amounts could be man-lifted onto the vehicle by several people, but larger amounts will require material handling equipment, which is concerning.

For the materials requiring heat to release the hydrogen (rGO-Mg, alane, MOF-5, and MCH), the energy required to heat the materials to a sufficient temperature to release the hydrogen was calculated. The energy required was then compared to the lower heating value of hydrogen to determine the percentage of hydrogen stored within the material used for the purpose of heating the material. MOF 5 utilizes only 0.6% of the hydrogen stored, while alane uses 1.4%, rGO-Mg uses 5.6%, and MCH uses 6.97%. In each case, the range of the vehicle will be impacted by this requirement because the percentage of hydrogen listed above will be utilized to heat the material rather than propel the vehicle, effectively reducing the amount of hydrogen stored in the system. To account for this, the amount of hydrogen stored on board will need to be increased. This leads to a recursive relationship, as increasing the amount of hydrogen stored will increase the mass of the system and therefore the vehicle, potentially requiring more fuel to meet the required range. This impact will be critical to understand as research into alternative propulsion continues.

The kinetics of the material-based hydrogen storage materials was investigated by modeling the kinetic performance of each material using models found in the literature. Each model was compared to the peak flow rate found in earlier vehicle modeling to determine if the material is suitable for each vehicle. Both rGO-Mg and MOF-5 were found to release hydrogen at a rate that meets the needs of each vehicle. MOF-5 was also able to uptake hydrogen at the same or higher rate than current technology, 60 g/s, while rGO-Mg was unable to maintain that flow for anything other than the two largest vehicles due to kinetic limitations. Alane did not immediately release hydrogen at the desired flow rate. There was a lag between 10 to 30 seconds, depending on the vehicle, consistent with the induction period observed by Graetz et al where hydrogen release is slower at low levels of fractional decomposition [8]. A lag in hydrogen release is not a desirable trait, but the model demonstrates that the required flow rates are met within a relatively short period of time. There are potential engineering strategies that can be used to compensate for the delayed time to full flow.

The model validates that MCH can be dehydrogenated at a fast enough rate to provide hydrogen to each vehicle under the most demanding conditions. The rate is controlled by the amount of catalyst in the system, which can be a significant factor for the system weight. This weight penalty varies between 5 and 19 percent of the mass of liquid needed to meet the required range. Like the energy requirements for the heater, the added mass of the catalyst will reduce the gravimetric density of the overall system, from 6.2 weight percent to between 5.2 and 5.9 weight percent. This still surpasses 700 bar compressed hydrogen but reduces the margin for any other components required to support the system, such as the reactor vessel. MCH may also require hydrogen purification after the dehydrogenation step, as the hydrogen may not meet the purity standards for fuel cell use.

Modeling also validated the performance of both the gaseous and cryogenic hydrogen systems. Pipe flow, heat transfer, and vaporization were modeled. All the systems saw no excessive pressure drops or flow restrictions when filling the vehicles with hydrogen or while providing hydrogen to the fuel cell.

Conclusion

This analysis has demonstrated that there are several technologies that can potentially outperform 700 bar compressed gas hydrogen storage, the current state of the art, when applied to military vehicles. When optimized for mass, volume, and ability to sustain the maximum flow of hydrogen in demanding conditions, it was found that cryo-compressed hydrogen provides the best performance. Compared with 700 bar compressed hydrogen, cryo-compressed hydrogen can store 160% of the hydrogen per unit weight and 300% more hydrogen per liter. The use of cryo-compressed hydrogen in the place of 700 bar compressed gas has the potential to reduce the cost of the storage vessel by reducing the amount of carbon fiber needed [4]. Cryo-compressed hydrogen can be refilled at a similar speed to current fuels, maintaining current readiness levels.

Several other technologies are worth investigation and have the potential to be future hydrogen storage methods for military ground vehicles. MOF 5 has incredibly fast kinetics and higher gravimetric and volumetric storage densities than compressed hydrogen gas. If the gravimetric density can be maintained near room temperature, MOF 5 systems could be less complex than both compressed gas and cryo-compressed while providing similar performance. Alane is also of interest due to its high gravimetric and volumetric hydrogen densities, however there may be challenges with loading and unloading large amounts of the material onto vehicles. This lends it towards smaller vehicle use, where less material is needed.

The simulations also found that rGO-Mg and MCH are potentially unsuitable for military ground vehicle application. Both rGO-Mg and MCH require 5% or more of the energy of the stored hydrogen to be released. There is a challenge with rGO-Mg meeting the filling time requirements for the vehicles. The smaller vehicles are unable to uptake hydrogen at a rate near the current state of the art. MCH also requires a catalyst, which reduces the gravimetric storage capacity compared to the other technologies. There is a chance the hydrogen coming from the MCH dehydrogenation reactor does not meet the purity requirements for hydrogen vehicles, requiring a purification step that will also add mass and volume to the system. The added challenge of storing two liquids onboard with an MCH system reduces its attractiveness. The toluene product from the dehydrogenation reaction will need to be stored onboard to be reprocessed offboard for future use. This added complexity is not present in the two leading technologies.

As military vehicles embrace electrification and its many benefits, this analysis shows that hydrogen fuel cells and advanced hydrogen storage technologies can play a role in future ground vehicle applications. While storing hydrogen as a compressed gas is the current state of the art, other technologies are quickly advancing and show potential to outperform it. Based on the encouraging results of the simulations performed, continued research into the applications of cryo-compressed hydrogen, MOF 5, and alane for military ground vehicle applications is recommended.

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