Power & Mobility (P&M)

Model-Based Optimization of Hydrogen Storage for Military Ground Vehicle Applications

Ben Paczkowski
Andrew Wiegand

Introduction

The Army has increasing interest in electrified vehicles:

- The Army Climate Strategy targets electrified vehicle platform fielding by 2035
- Electrification enables:
  - Silent watch
  - Silent mobility
  - Advanced sensor and weapon packages
  - Exportable power
  - Microgrids

https://www.trucks.com/2017/04/03/chevrolet-zh2-hydrogen-truck/

Fuel cells can fill gaps in current electrification technologies

- Fast fueling on par with current fueling times
- Extended range operations
- Utilize logistic fuels (direct fuel or fuel to hydrogen)

Hydrogen stored on military vehicles is a challenge

- Lower volumetric density than liquid fuel

Scope: Vehicles

Vehicles were selected to cover a broad range of weight classes from around 10,000 kg to 50,000 kg both wheeled and tracked:

- 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 (MPF) Prototype
- M88 Recovery Vehicle

https://www.nationaldefensemagazine.org/articles/2022/1/25/oshkosh-defense-unveils-new-hybrid-electric-jltv

https://oshkoshdefense.com/vehicles/medium-tactical-vehicles/fmtv/

https://oshkoshdefense.com/vehicles/heavy-tactical-vehicles/pls/

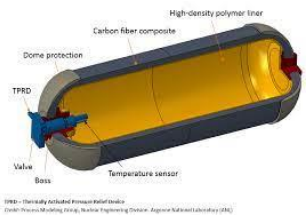
https://www.army-technology.com/news/allison-us-propulsion-systems-m113/

https://www.baesystems.com/en-us/product/m88a2-hercules-recovery-vehicle

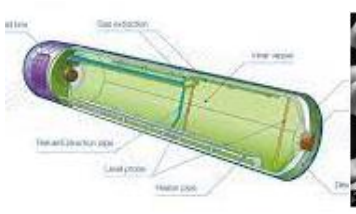
Scope: Hydrogen Storage

A variety of technologies were investigated including:

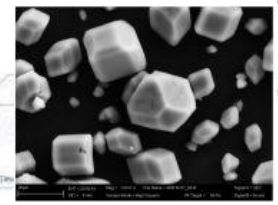
- 350 and 700 bar compressed gaseous storage (state of art)
- Liquid hydrogen (LH_2)
- Cryo-compressed hydrogen (CcH_2)
- Aluminum hydride (alane)
- Magnesium nanoparticles encapsulated in reduced graphene oxide (rGO-Mg)
- Metal organic framework 5 (MOF-5)
- Methylcyclohexane (MCH)/toluene liquid organic hydrogen carrier (LOHC)



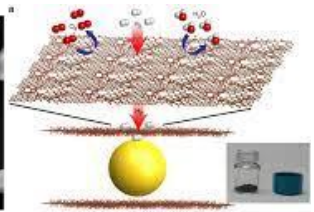
https://www.energy.gov/eere/fuelcells/physical-hydrogen-storage



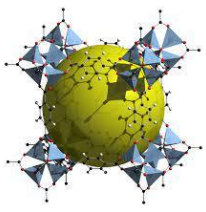
https://www.airbus.com/en/newsroom/news/2021-12-how-to-store-liquid-hydrogen-for-zero-emission-flight



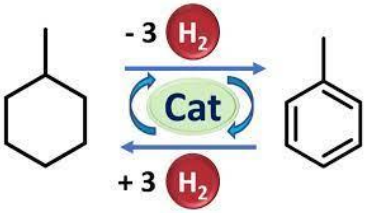
http://dx.doi.org/10.1016/j.ijhydene.2014.01.167



https://doi.org/10.1038/ncomms10804



https://doi.org/10.1126%2Fscience.1083440



https://doi.org/10.3390/en15249

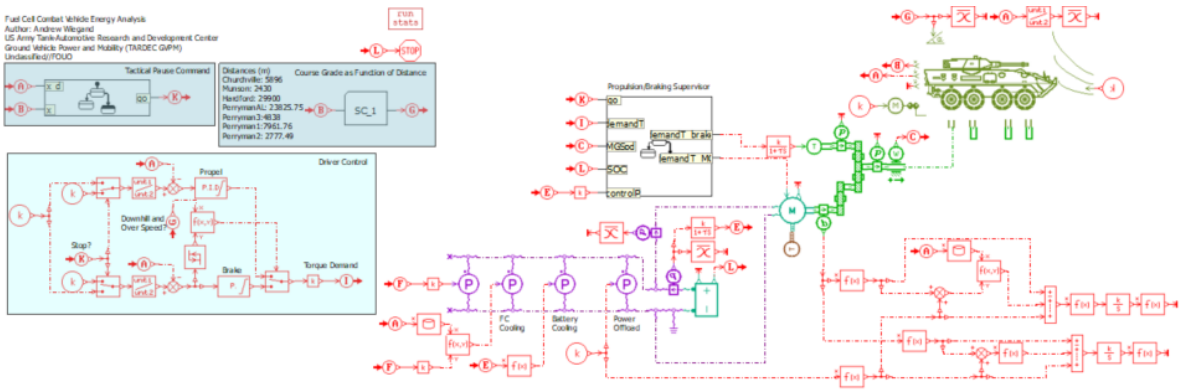
Assumptions

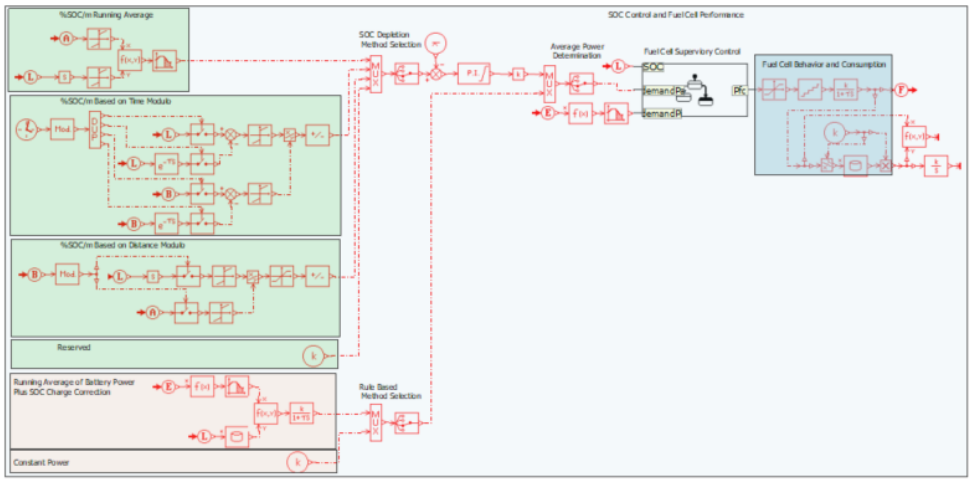
- 1 polarization curve used to define fuel cell performance for all vehicles
- Same active area per cell in each vehicle
- Cells connected as a stack to match current vehicle power
- Fuel cell and battery hybrid system
  - Battery capacity determined by the kinetic energy of 70 mph to 0 deceleration
- Hydrogen storage technologies at same operating temperature and pressure, where possible
- One dimensional vehicle model based on road load equation:

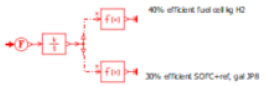
$$Load = f_r mg\ cos\theta + \frac{1}{2}\rho_{air} c_d A v^2 + mgsin\theta$$

- Charge sustaining battery control strategy
- All vehicles weight neutral after fuel cell conversion

Model


Fuel Cell Combat Vehicle Energy Analysis
Author: Andrew Wiegand
US Army Tank-Automotive Research and Development Center
Ground Vehicle Power and Mobility (TARDEC GVPM)
Unclassified//FOUO
Tactical Pause Command
Course Grade as Function of Distance
SC_1
Driver Control
Propel
Brake
Torque Demand
Propulsion/Braking Supervisor
demandT
demandT brake
demandT MC
SOC
controlP
FC Cooling
Battery Cooling
Power Offload


%SOC/m Running Average
%SOC/m Based on Time Module
%SOC/m Based on Distance Module
Reserved
Running Average of Battery Power Plus SOC Charge Correction
Constant Power
SOC Depletion Method Selection
Rule Based Method Selection
SOC Control and Fuel Cell Performance
Average Power Determination
Fuel Cell Supervisory Control
SOC
demandPfc
demandPt
Pfc
Fuel Cell Behavior and Consumption


40% efficient fuel cell kg H2
30% efficient SOFC+ref, gal JP8

Submodels

- Kinetic models:
  - rGO-Mg: Johnson-Mehl-Avrami (JMA)
  - Alane: Avrami-Erofeyev
  - MOF-5: classic micropore diffusion
  - MCH: Langmuir-Hinshelwood-Hougen-Watson (LHHW)
- Amesim Submodels:
  - Real gas flow
  - Constant volumetric liquid flow
- Shell and tube heat exchanger design equations

Vehicle Parameters

Vehicle Designator	Weight (approx.)	Required Range	Frontal Area	Drag Coefficient	Rolling Resistance		
Units or Condition	kg	mi	m^2	Dimensionless	Primary	Secondary	Cross Country
M1280	9,000	300	5.16	0.7	0.008	0.016	0.071
M1085	21,000	300	5.11	0.75	0.009	0.016	0.071
M1075	40,500	300	4.46	0.95	0.009	0.016	0.071
M113	15,000	300	6.28	0.68	0.045	0.055	0.076
MPF	20,500	300	7.53	0.66	0.038	0.057	0.076
M88A1	51,000	280	9.71	0.95	0.06	0.06	0.06

Simulation Results

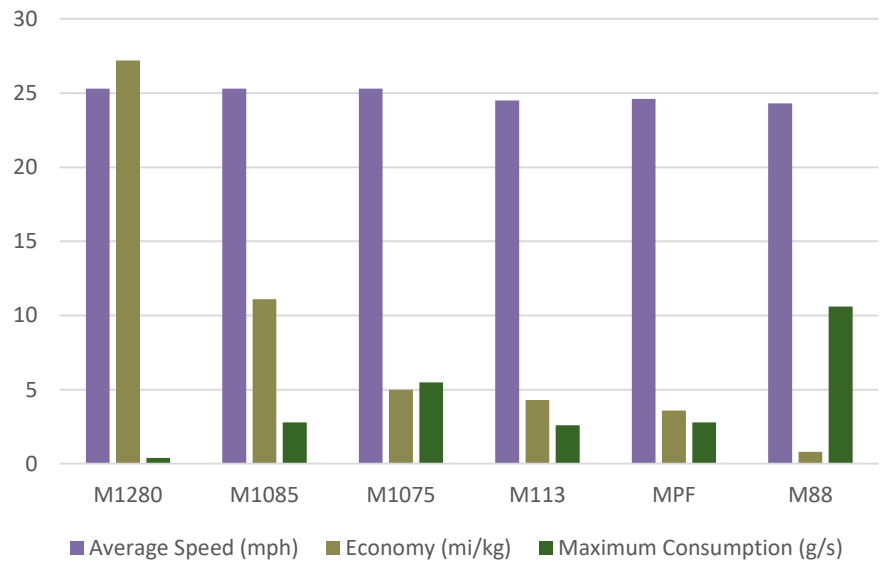
Vehicle	Speed (mph)	Economy (mi/kg)	Required Range (mi)	Required H_2 Storage (kg)
M1280	35	23.2	300	12.9
M1085	35	10.6	300	28.4
M1075	35	6.7	300	44.7
M113	25	3.8	300	78
MPF	25	3.3	300	91
M88A1	20	0.88	280	318.9

Conditions:

- 0% grade (flat)
- 10 mile primary road

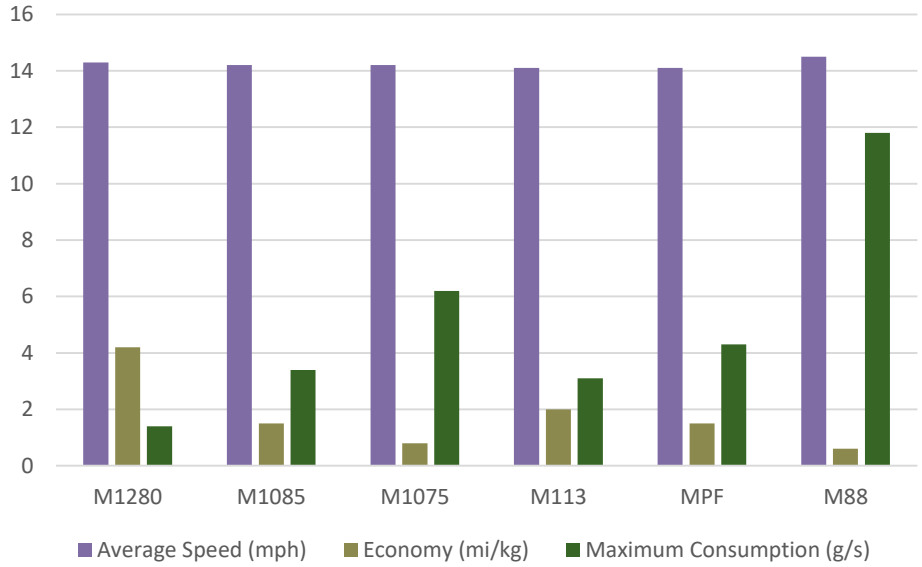
Simulation Results

MUNSON SIMULATION RESULTS



- Primary road with one hill
- 25 mph target speed
- 120 kW regen braking limit

CHURCHVILLE SIMULATION RESULTS



- Aggressive cross country
- 15 mph target speed
- Same braking and controls as Munson

Hydrogen Storage System Mass

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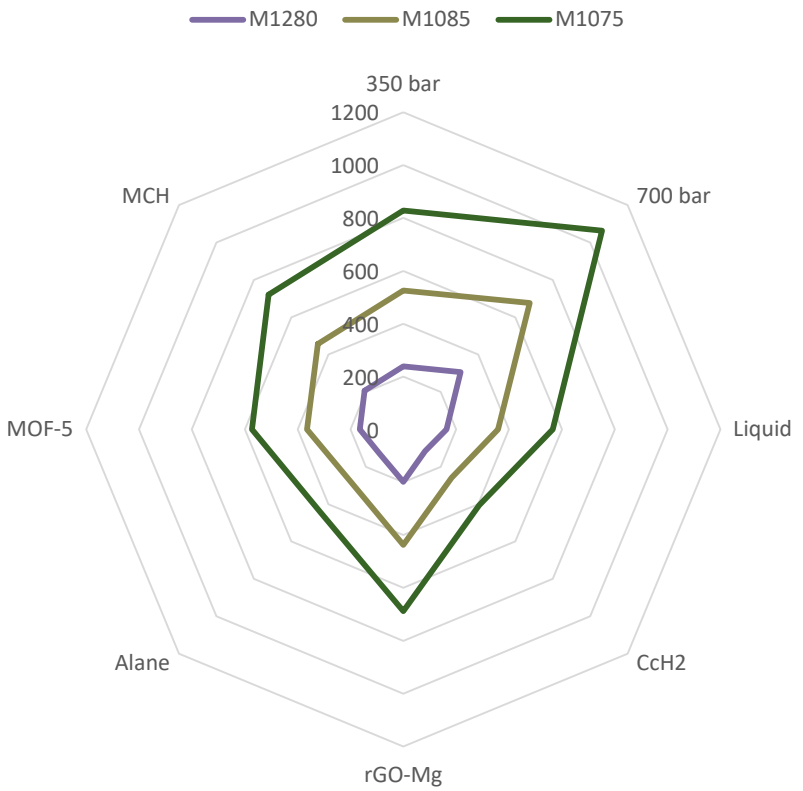
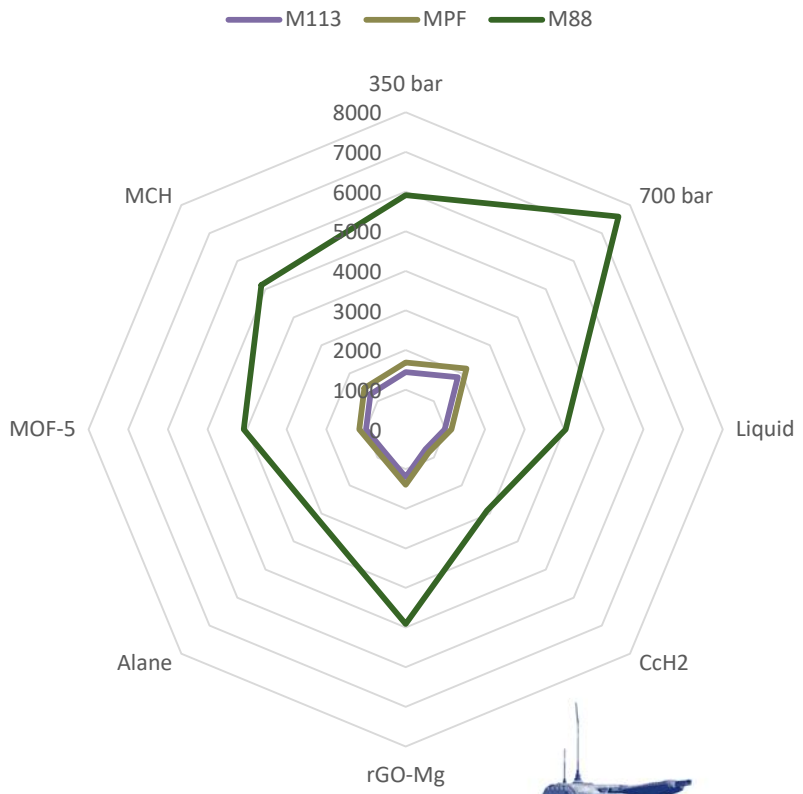
WHEELED VEHICLE HYDROGEN STORAGE MASS (KG)

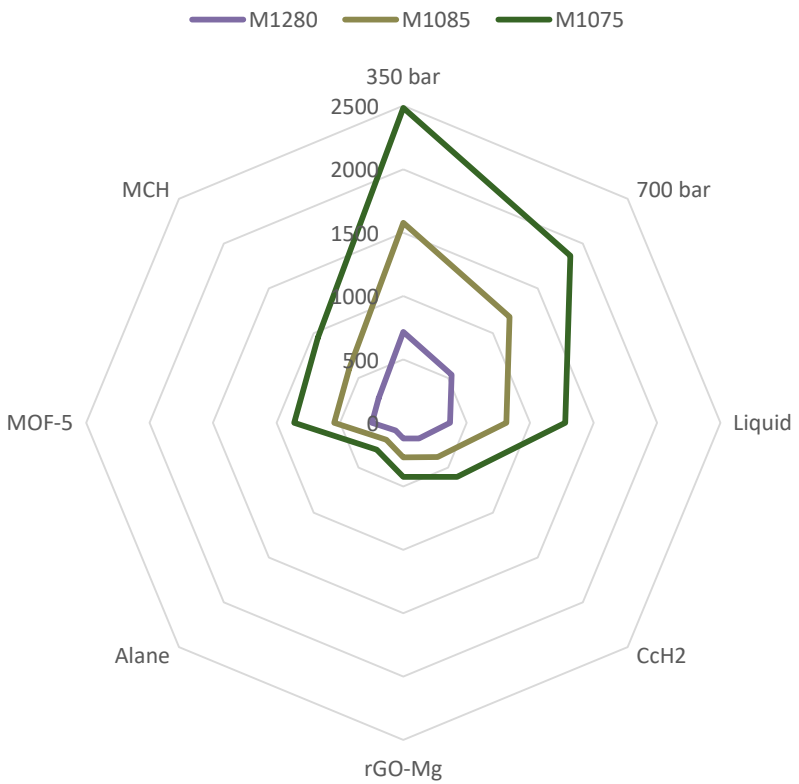


TRACKED VEHICLE HYDROGEN STORAGE MASS (KG)

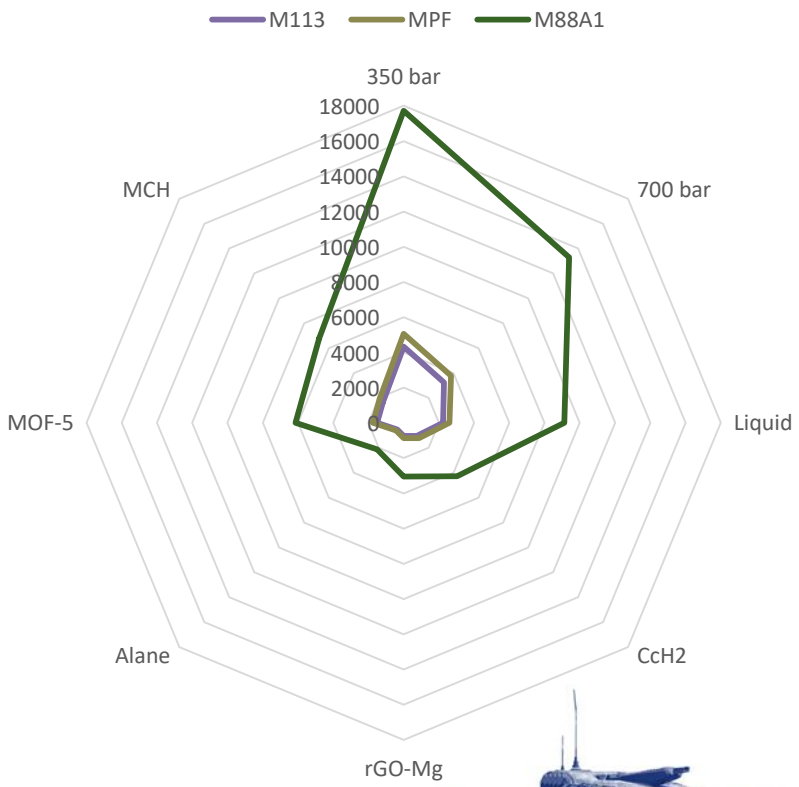


Hydrogen Storage System Volume

WHEELED VEHICLE HYDROGEN STORAGE VOLUME (L)



TRACKED VEHICLE HYDROGEN STORAGE VOLUME (L)



Hydrogen Flow from Materials

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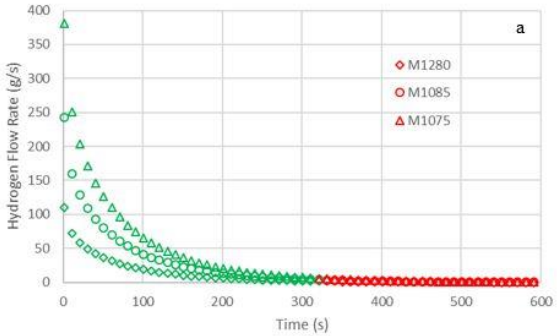
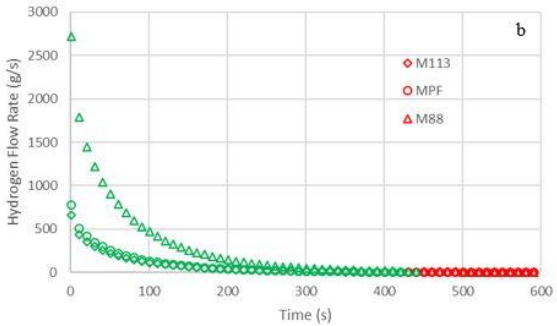
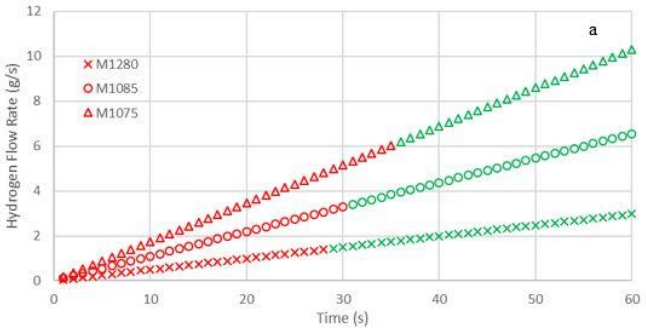
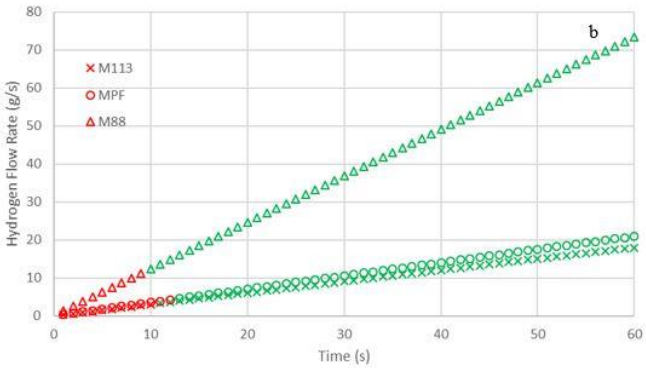


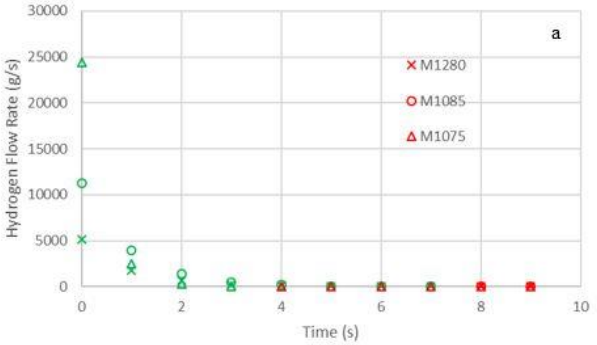


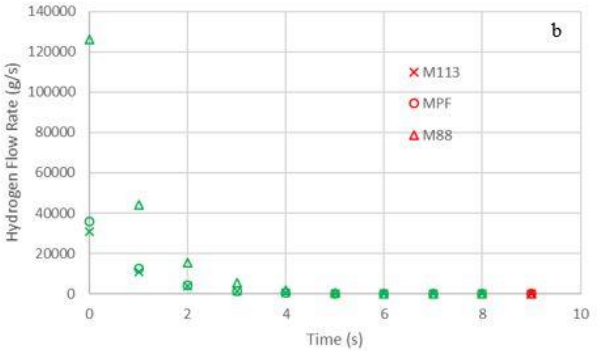
rGO-MG





Alane

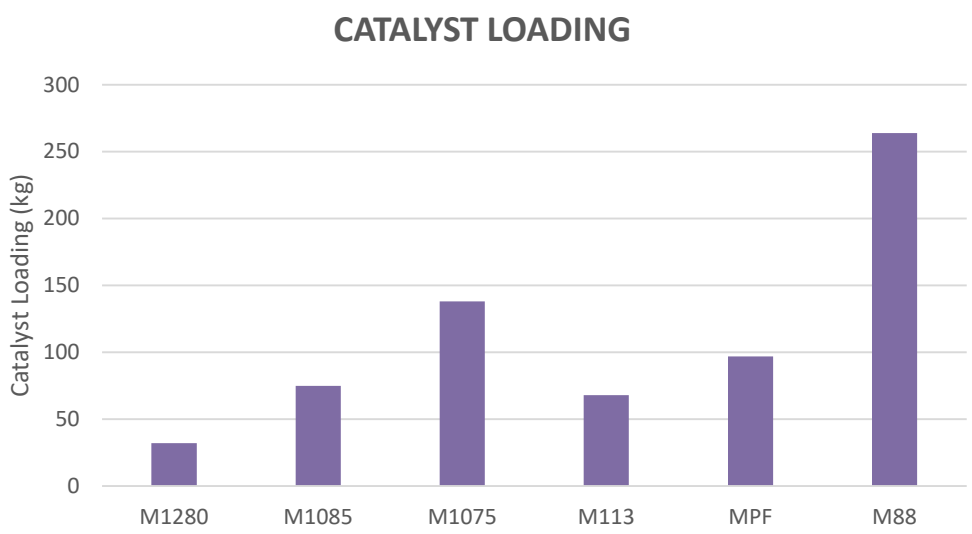


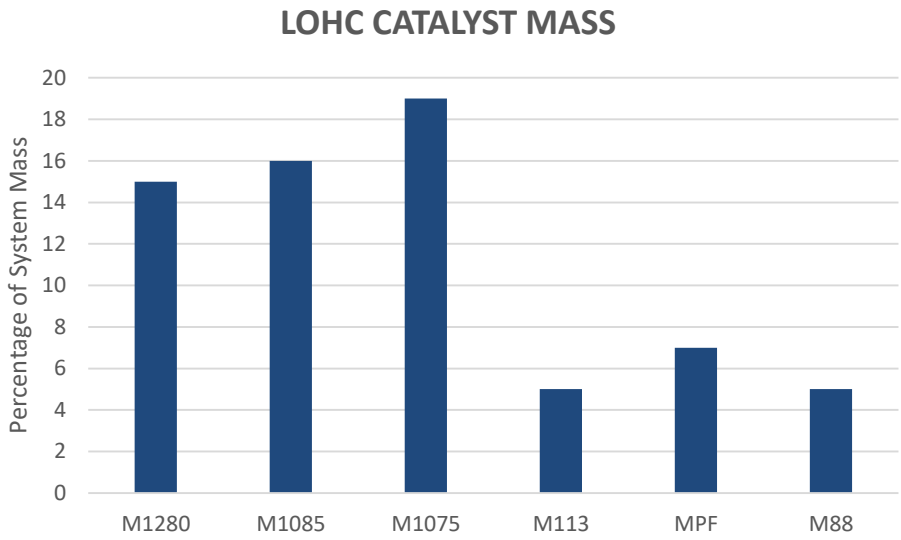


MOF-5

Green meets or exceeds flow rate requirements, red does not. Wheeled vehicles above, tracked vehicles below.

LOHC Requirements





- Accounting for catalyst mass, the MCH system has a higher gravimetric density than 700 bar compressed hydrogen
- However, the margin could be reduced with the addition of storage tanks and hydrogen purification systems

Heat Transfer Considerations

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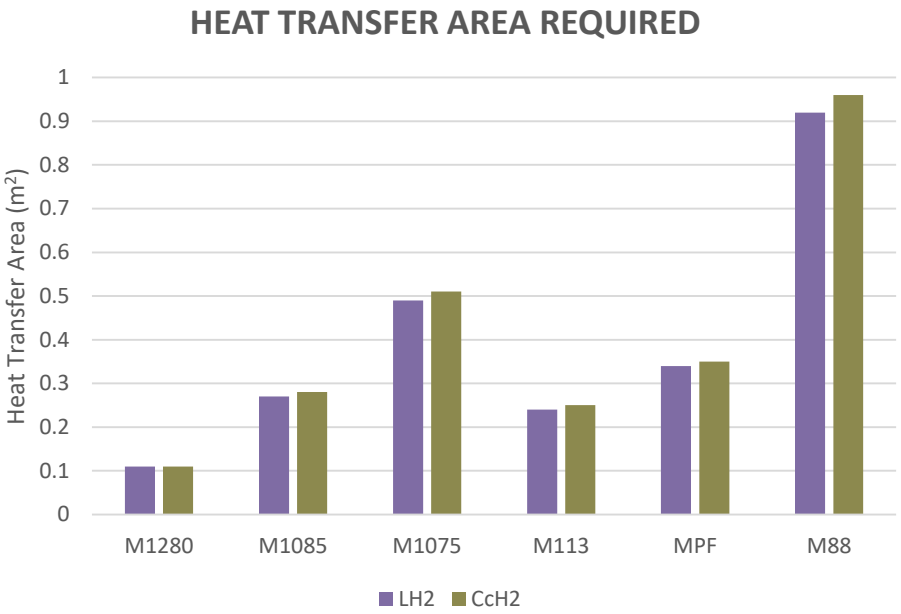

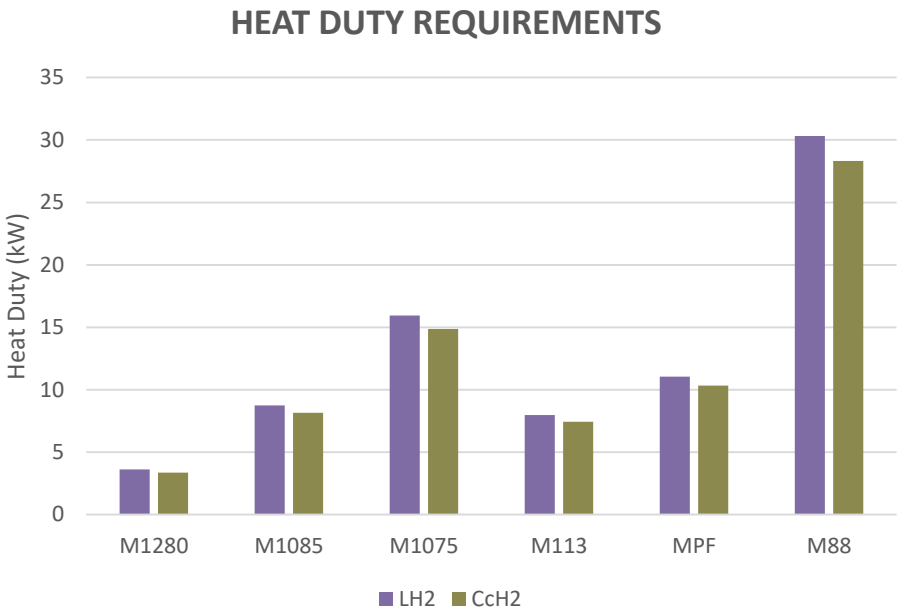

- Heat exchangers can handle the required flow rates for all vehicles with minimal pressure drop
- CcH2 requires slightly more heat transfer area due to the 40 K temperature difference
- This difference reduces the heat duty for CcH2

Conclusions

- Fuel cell systems can provide adequate power for all investigated systems
- Several technologies can outperform the state of the art
  - Cryo-compressed can store 160% more hydrogen per unit weight, 300% more per unit volume
  - MOF-5 has incredible kinetics and could offer a simplified design
  - Alane has impressive gravimetric and volumetric capacities
- rGO-Mg and MCH present challenges
  - Both require at least 5% of the total energy stored to be utilized
  - rGO-Mg may not meet filling time needs
  - Hydrogen from MCH may need purification
  - MCH requires two liquids to be stored on vehicle and is complex