The Wolverine: Design and Analysis of a Hydrogen Fuel Cell HEV Class 8 Semi-Truck

AUTO 566: Final Project Report – Team 4

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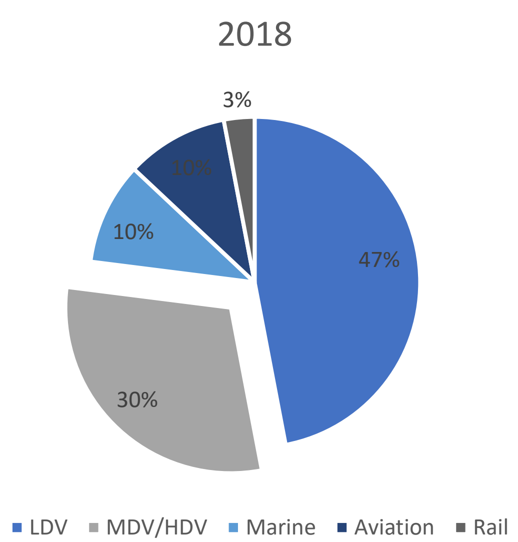
Introduction

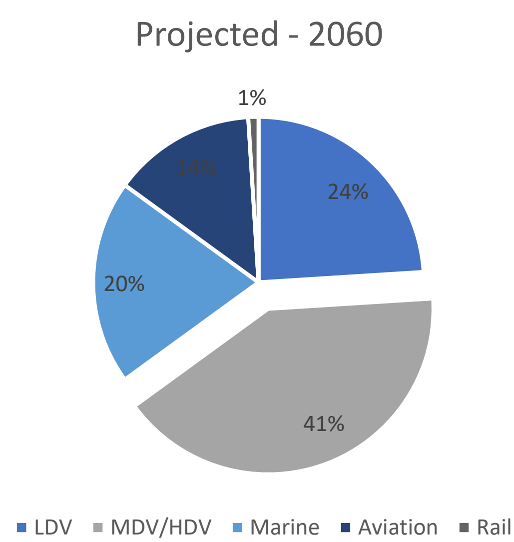
1.1 Problem

51 billon tons of greenhouse gases are released into the atmosphere every year [1]. In 2015 the United Nations launched Mission Innovation, a global effort to accelerate the development of green energy technologies, which developed the following 5 classifications for greenhouse gas emissions:

Making things (cement, steel, plastic)	31%
Plugging in (electricity)	27%
Growing things (plants, animals)	19%
Getting around (planes, trucks, cargo ships)	16%
Keeping warm and cool (heating, cooling, refrigeration)	7% [1]

16% (8.16 billion tons) of total global emissions are attributed to the transportation industry of which 30% (2.448 billion tons) are from medium and heavy-duty trucks (MDV/HDV). The proportion of emission attributed to MDV and HDV is projected to rise to 41% by 2060 according to the International Council on Clean Transportation (ICCT) [2].





To reduce emissions and fight climate change, technologies must be developed and implemented in the transportation system on a global scale while maintaining profitability and increasing the reliability of the vehicles. Implementation of hydrogen fuel cell technologies in different vehicles is an option for reducing emissions if the process for producing hydrogen becomes cleaner and more efficient. Methods like hydrogen synthesis by light are very promising [43].

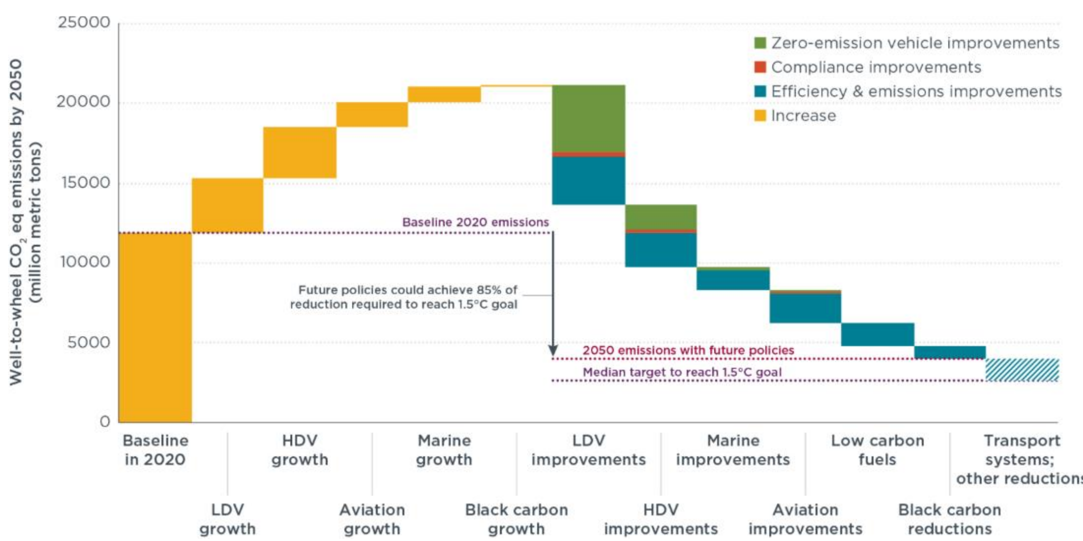
In this study the implementation of hydrogen fuel cell technology for semi-trucks is explored using a 1-dimensional physics model of the vehicle. Parameters were developed to match the vehicle application and a control algorithm was implemented to optimize efficiency.

1.2 Needs and Benefits

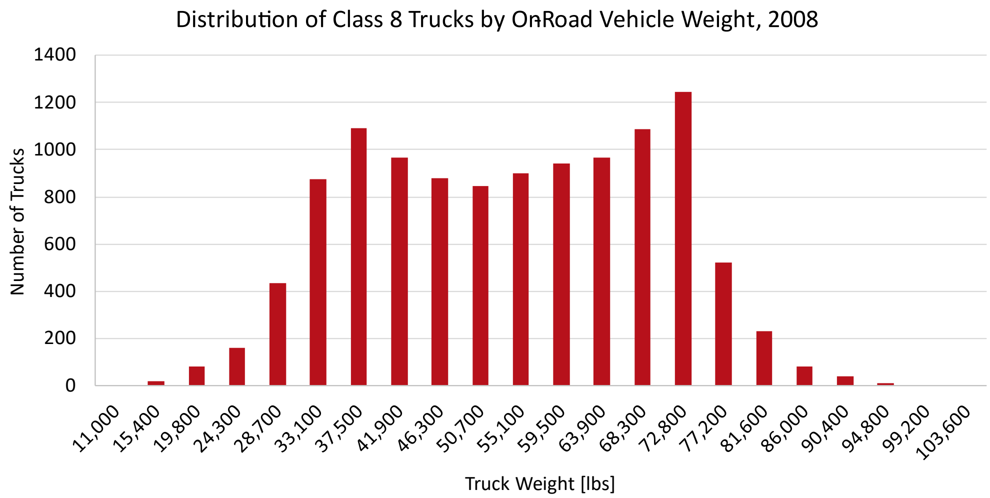
As the transportation industry addresses the problem of climate change they must do so while maintaining the ability to transport goods throughout the world. This means that any solution that is identified must conform to the demands of the industry.

To show the needs, benefits, and opportunity areas of hydrogen fuel cells key parameters for industry and environment are compared for diesel, battery, and hydrogen fuel cells for class 8 semi-trucks. The data shown in the charts below has been aggregated from several different references found during the investigation process to draw conclusions about the general trends in the powertrain composition for our application.

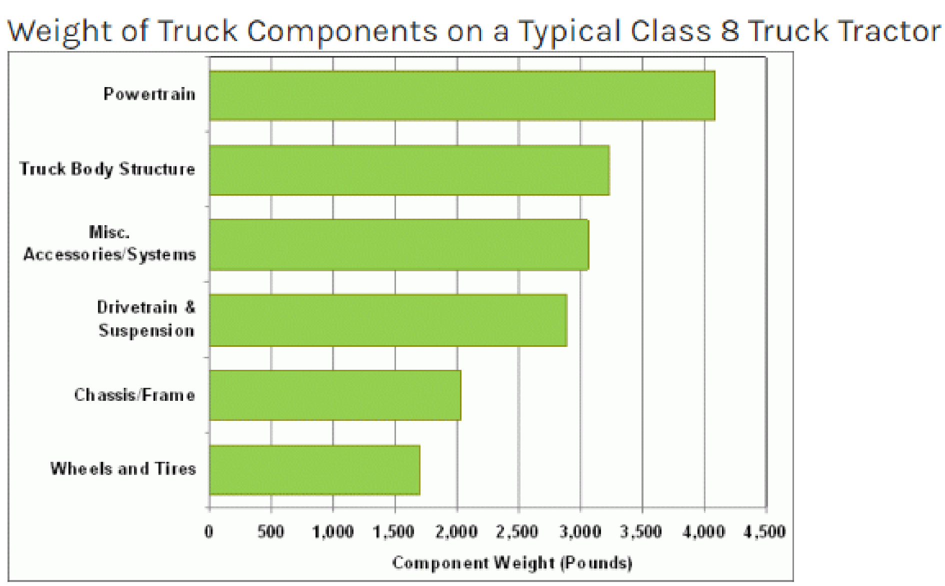
Emissions must be reduced to fight climate change and regulators are responding by tightening the requirements on the trucking industry with the goal of achieving zero emissions. This would result in a 5% reduction of global emissions each year. The chart below [3] illustrates a proposed path for reducing the emissions for the transportation sector by 2050. However, the goal of reducing transportation emissions by 85% from 2020 to 2050 cannot be achieved without a significant contribution from the trucking industry. Those contributions will come from efficiency & emissions improvements, compliance improvements and zero-emissions technologies as shown in the chart below.



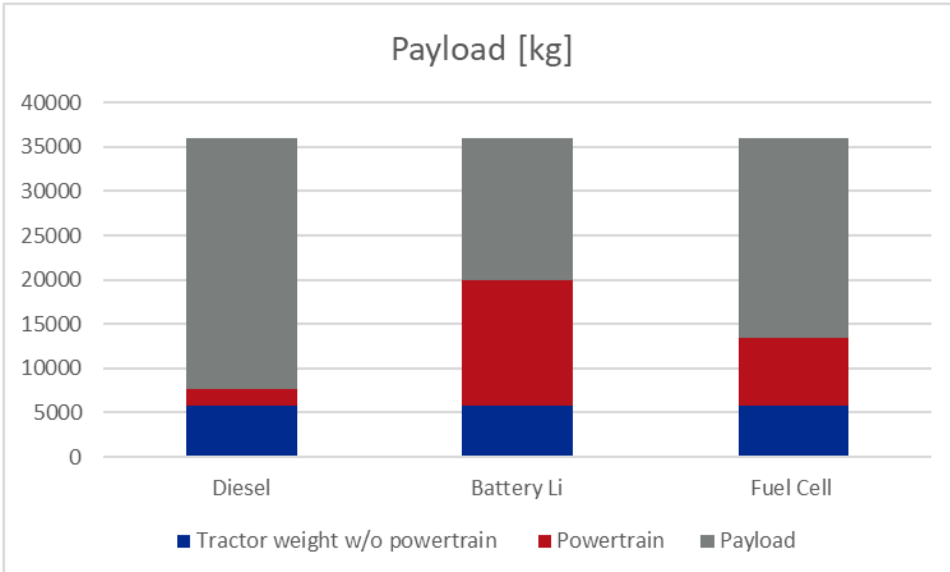
Payload capacity is crucial for the trucking industry. Its profitability depends on how much the truck can transport. Current diesel class 8 trucks can transport a payload up to 28000 kg. The chart below comes from the National Renewable Energy Laboratory (NREL) [6] and shows the gross weight distribution from a study ran for class 8 semi-trucks; it can be observed a vehicle supporting a payload of 73,000 [lbs.] would satisfy the needs of 90% of the industry.



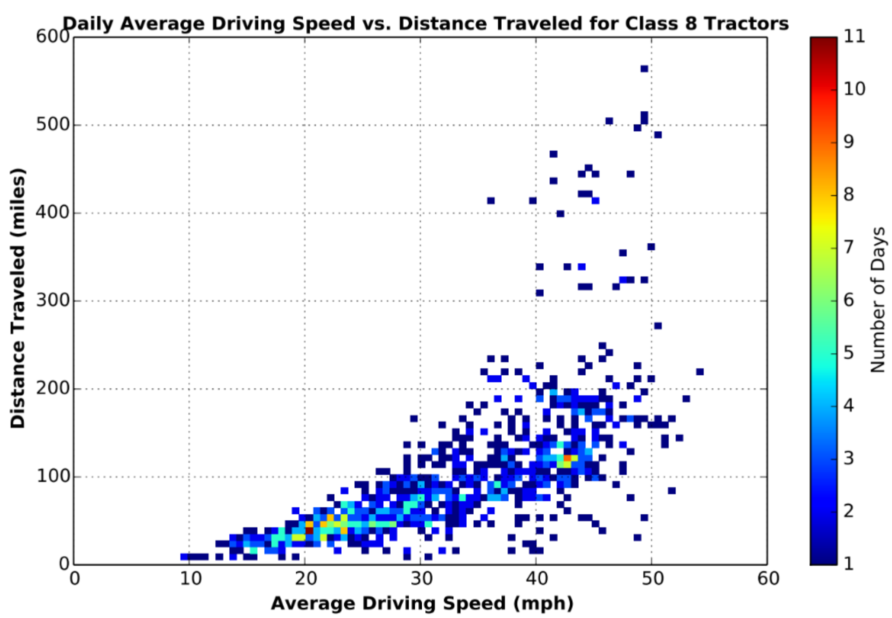
Regulations for class 8 vehicles limit the total gross weight to 36,000 [kg]. This hard cap on weight means that every kilogram added to the powertrain takes away a kilogram that could be transporting goods and making a profit. The next plot from the Department of Energy (DOE) shows a breakdown of the tractor weight [8]:



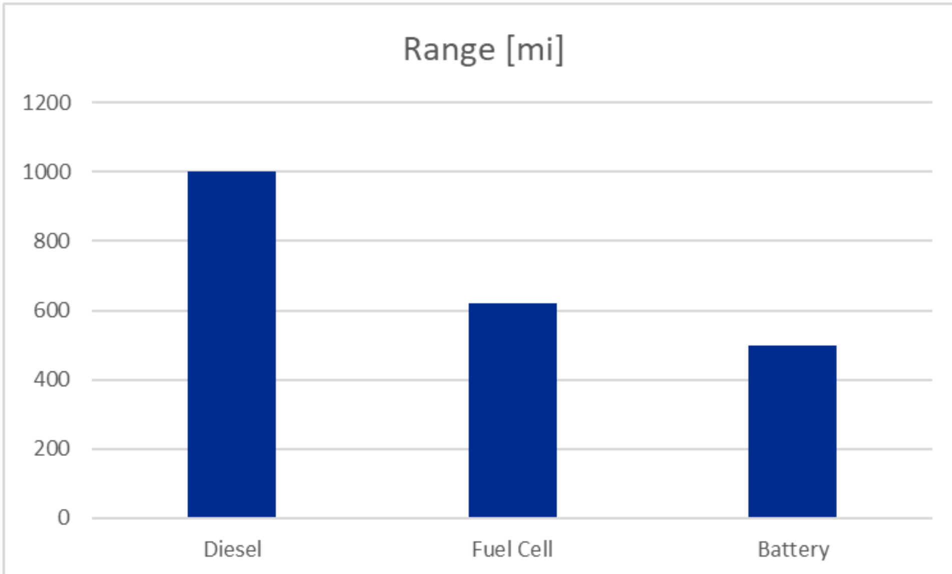
The average weight of a diesel semi-truck's tractor is 8000 [kg]. From the plot above the diesel powertrain weights 1900 [kg] (4100 [lbs.]). The rest of the tractor's weight is 5800 [kg], this will be a constant during the comparison of different power systems, Diesel, battery, and fuel cell + battery. Payload data from battery was taken from the article "Quantifying the Economic Case for Electric Semi-Trucks" [9] where a full battery powered vehicle with a range of 500 miles and 1000 [kWh] battery with an estimated payload capacity of 16 – 19 tons (14500 – 17000 [kg]). A middle value was considered for the plot below 16000 [kg]. For fuel cell truck payload comes from the Daimler website in an article about its fuel cell GenH2 truck with a payload capacity of 25 tons (22500 [kg]) and a range of 620 miles [10].



In terms of range the average annual distance traveled by a class 8 truck for the first five years of operation is 100,000 miles and the annual average mileage for the semi-truck in the United States is 75,000 miles [4]. Based on the analysis of the operational cost of trucking from 2017, 40% are known to travel between 100-500 miles, with another 40% traveling greater than 500 miles [5]. The National Renewable Energy Laboratory also conducted a study where 70 trucks were monitored for 1150 days and tracked several significant factors. The plot bellow shows the distance traveled vs average speed and number of days on the road [6].



Diesel truck range for comparison is 1000 miles, a figured obtained from an article about Class 8 hybrid-electric truck Technologies [11]. The range for battery and fuel cell vehicles, where obtained from the reference sited in the previous paragraph [9][10].



The cost of the energy system comes from two tables [7][12]. Calculation for battery cost was straight forward. Li-ion battery cost in the table below and the 1000 kWh capacity for a 500 miles range described before. Calculation for fuel cell system required more data found in second table below, from this table cost projected for 2030 was used. It was considering the fuel cell system cost plus the Hydrogen storage system cost plus the battery cost. Capacities of the system were taken from the GenH2 truck.

Table 1. Bounds and Mean Values of Variables

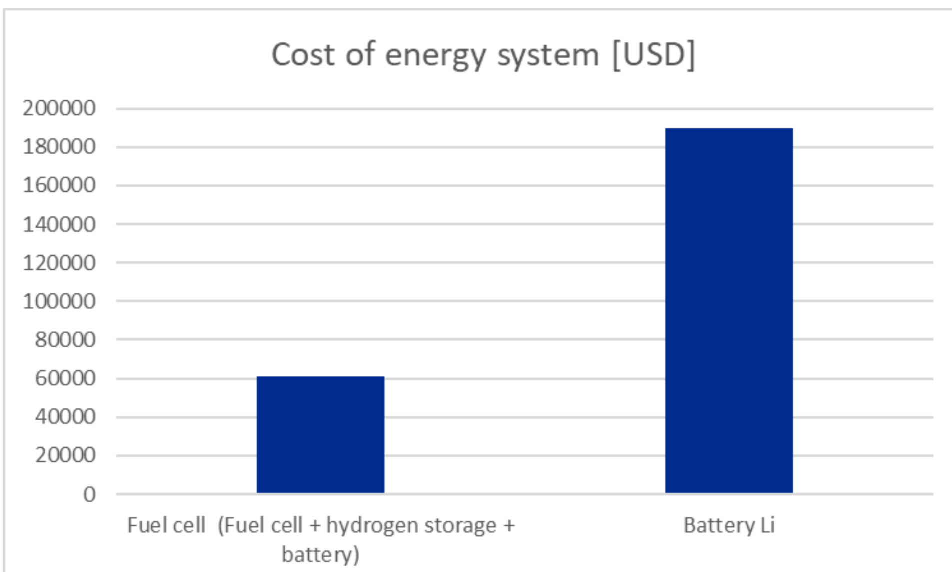
parameter	[bounds], mean
C_d	[0.45, 0.7], 0.63
C_{rr}	[0.0045, 0.01], 0.0063
W_T (1000 kg)	[27, 36], 32
W_V (1000 kg)	[7, 10], 8
v (m/s); (mph)	[16, 21], 19; [36, 47], 43
v_{rms} (m/s); (mph)	[19, 24], 22; [43, 54], 49
$Cost_{kWh}$ Li-ion ($/kWh)	[150, 300], 190
$Cost_{kWh}$ beyond Li-ion ($/kWh)	[80, 200], 120
S_P Li-ion (Wh/kg)	[220, 300], 243
S_P beyond Li-ion (Wh/kg)	[350, 700], 500

Table 1. Technical System Targets: Class 8 Long-Haul Tractor-Trailers (updated 10/31/19)

Characteristic	Units	Targets for Class 8 Tractor-Trailers	
		Interim (2030)	Ultimate[9]
Fuel Cell System Lifetime[1,2]	hours	**25,000**	**30,000**
Fuel Cell System Cost[1,3,4]	\$/kW	**80**	**60**
Fuel Cell Efficiency (peak)	%	**68**	**72**
Hydrogen Fill Rate	kg H_2/min	**8**	**10**
Storage System Cycle Life[5]	cycles	**5,000**	**5,000**
Pressurized Storage System Cycle Life[6]	cycles	**11,000**	**11,000**
Hydrogen Storage System Cost[4,7,8]	\$/kWh (\$/kg H_2 stored)	**9 (300)**	**8 (266)**

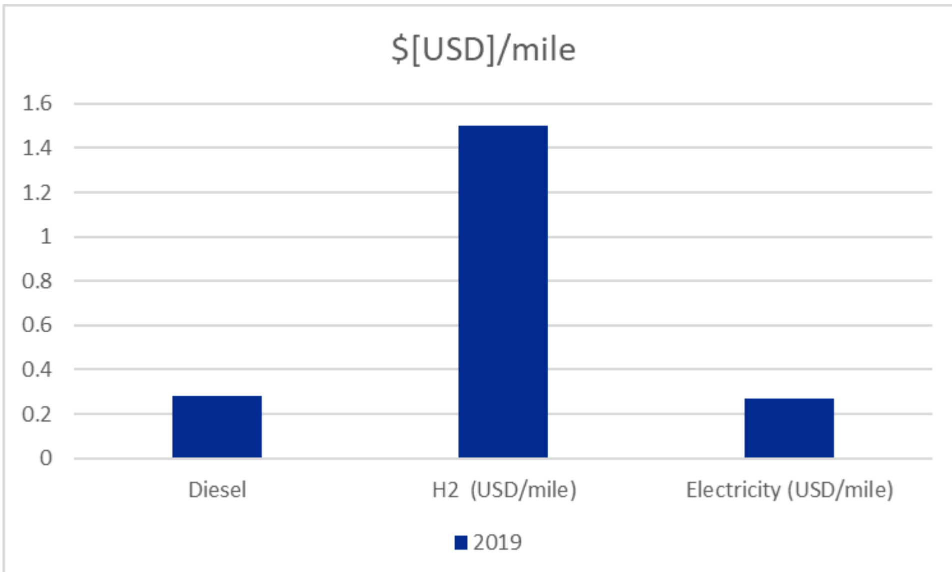
Mercedes-Benz GenH2 Truck specs:

- range of **up to 1,000 km (620 miles)**
- 80 kg (2x 40 kg) of liquid hydrogen
- 300 kW of hydrogen fuel cells power output (2x 150 kW)
- 70 kWh battery with temporary power output of up to 400 kW
- two electric motors
  continuous output of 2x 230 kW and 2x 1,577 Nm of torque
  peak output of 660 kW (2x 330 kW) and 2x 2,071 Nm of torque
- target gross weight of 40 tons (25 tons of payload)

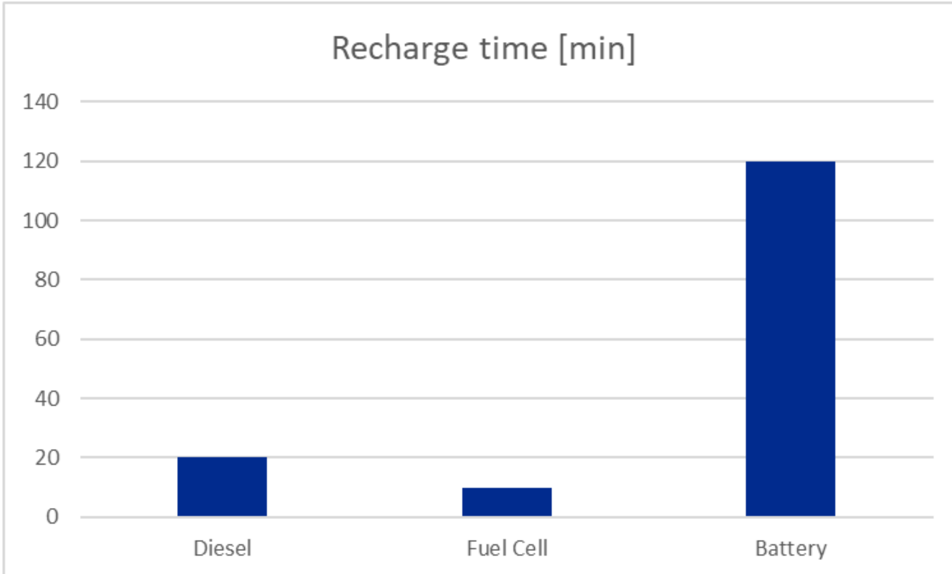


Fuel cost per mile is the next key parameter. Cost of diesel and hydrogen per mile were obtained from the US Department of Energy in a text where diesel VS Hydrogen tuck technologies were compared [12]. Electricity cost per mile comes from the table shown below [9]. Multiplying the high values of the E-truck efficiency and the electricity price provides a cost of 0.27 USD/mile.

Initial Price Differential	US$100,000[18,35,36]
E-Truck, Efficiency	[1.8-2.3]kWh/mi
D-Truck, Efficiency	[6-8.5]mpg[7,16,17,27]
General Op–Costs	US$[0.65-0.87]/mi[16,27]
D-Truck, Additional Repairs	US$[0.12-0.16]/mi[16]
Diesel Price	US$[2.2-4.2]/ga[32,33]
Electricity Price	US$[0.07-0.12]/kWh[33,34]
Annual Mileage	[80,000-100,000]mi[7,17]
Discount Rate	3%



For fuel recharge time data was taken from an analysis done by the Transport and Environment organization. The recharge time in 2030 is projected to be 10 to 20 min [13]. In the case for electric trucks of the same size they also provide a charging time of 8 hours, a more competitive time was found for Nikola TRE BEV of 120 min for 80% SOC, data was taken from Nikola home page [14].



Long distances and heavy payloads require larger and heavier batteries, resulting in diminishing performance and efficiency. Fuel cell electric vehicles, on the other hand, can travel farther and carry more weight than their battery electric counterparts as previous data has shown. Fuel cell electric vehicles have a much higher energy density by weight, allowing them to overcome the range and weight challenges associated with battery electric vehicles. Due to the current density of fuel cells, starting at low percentages of load, they are also able to produce a higher thermal efficiency. It immediately jumps to a high thermal efficiency and can maintain it through a 20% and 40% load, which is where the average bus and truck power is. This is more than the likes of gas- and diesel-powered trucks [26]. Fuel cell electric vehicles can be refueled within minutes. This results in significantly less downtime than other alternative power solutions. For the diesel versus fuel cell comparison, its main advantage is less emissions while driving and a little more competitive refueling time. For emissions it is important to remark that the highest benefit for hydrogen will only be realized after a transition from blue to green hydrogen production.

A hydrogen fuel cell hybrid electric vehicle satisfies the needs of reducing emissions while increasing efficiency and cost effectiveness for the industry and offers comparable or increased performance for other clean architectures.

1.3 Competition

To find an optimal solution to our approach, it was necessary to benchmark the competition in various electric and hybrid technologies in the class 8 semi-truck market. There are a handful of companies attempting to expand in this area including Nikola, Tesla, and Mercedes-Benz which are presented in the table below. What is also included is data found on diesel semi-trucks and a hypothetical fuel cell electric vehicle developed in ACS Energy Letter's report on Performance Metrics Required of Next-Generation Batteries to Make a Practical

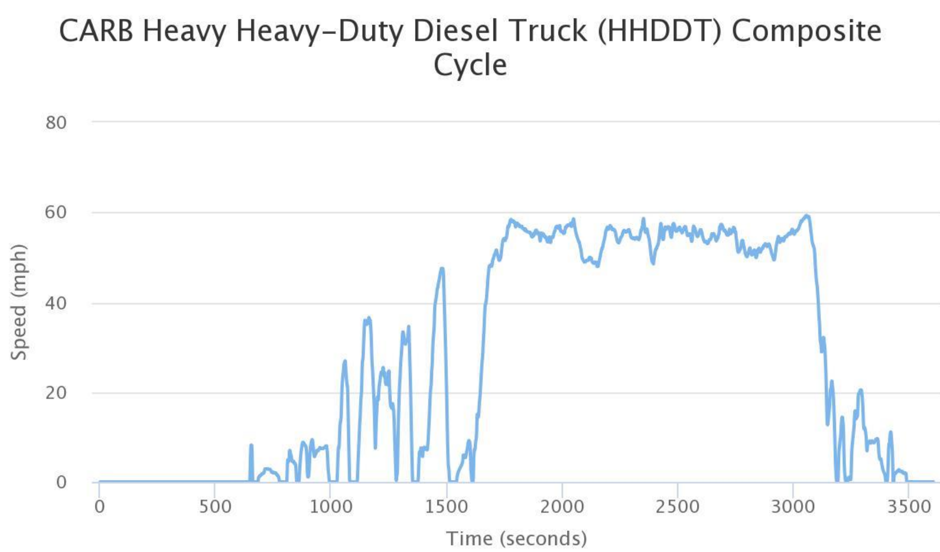
Electric Semi-Truck [15]. The metrics that were compared between the competition are range, payload, maximum driving speed, energy consumption, power, and recharge time. These metrics are not only important for guiding the implementation of the model and simulation, but also important in the eyes of customers.

	Diesel	Nikola Tre BEV	Nikola Tre FCEV	ACS Energy Optimal FCEV	Tesla Semi	Mercedes-Benz GenH2 Truck
Range [mi]	1000	350	500	600	500	620
Payloads [lbs.]	62,000	-	-	53,000	-	48,000
Maximum Speed [mph]	85	75	-	-	60	75
Energy Consumption [kWh/mi]	4.45 - 6.3	-	-	1.9	2	-
Power [kW]	350 – 500	480	480	-	745	400
Recharge Time [min]	20	120 (10-80% SOC @ 240 kW)	20	-	30 (80% SOC)	10

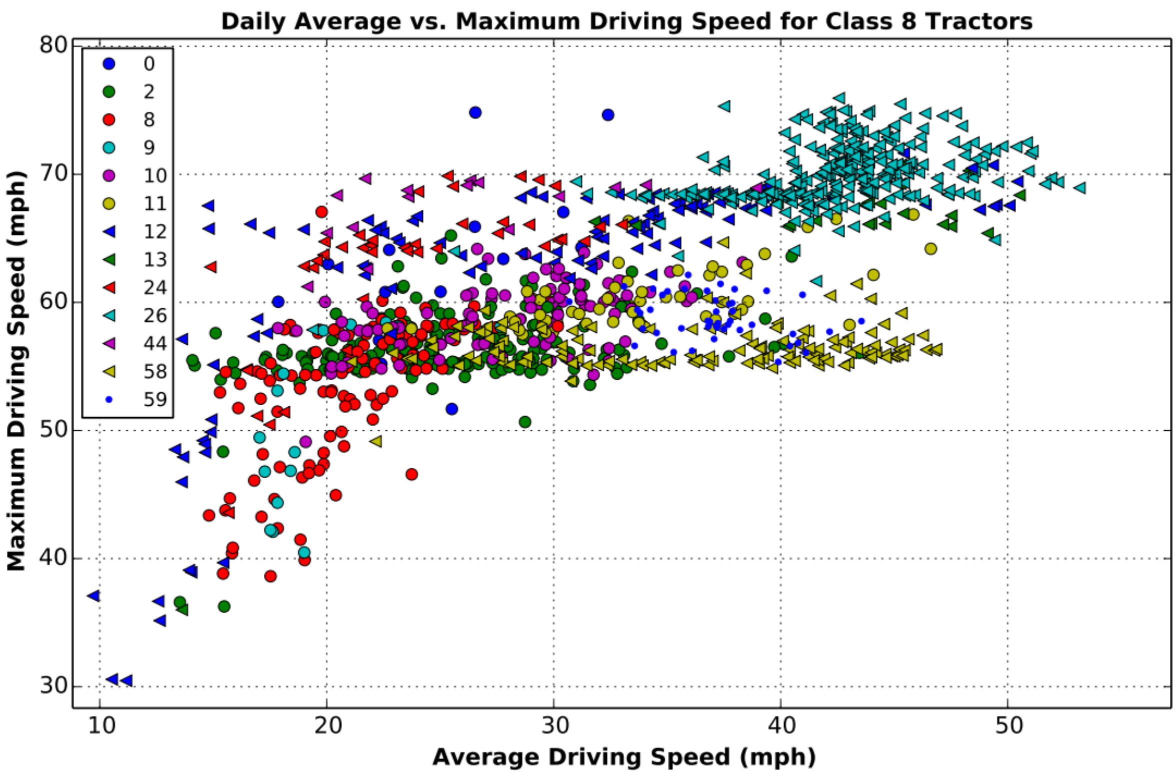
Table 1 Competitive analysis of diesel, battery electric, and fuel cell electric class 8 semi-trucks [15][26][27][28][29][30].

1.4 Approach

The National Renewable Energy Laboratory (NREL) maintains a directory of drive cycles which are based on real-world vehicle operation and can be used for the evaluation of vehicle systems. This dataset contains specific drive cycles, developed by the California Air Resource Board, for Heavy Duty Diesel Trucks which directly applies to our application of a class 8 semi-truck [42]. The drive cycle is broken up into three segments: Creep, Cruise, and Transient. To determine the overall performance of our vehicle we chose to iterate and validate the controls model on the composite cycle which combines all three subsections into a single drive cycle.



NREL also provided a Fleet DNA Project Data Summary Report which highlighted graphical data summaries that cover specific statistical trends from past DOE fleet studies. The charts below were created to present the daily average driving speeds and daily maximum driving speeds between 70 trucks. Both metrics are correlated amongst a set population of several types of fleet vehicles. From this data we determined the range of operational speeds that can be expected for semi-truck applications and tailored the final drive ratio so that our vehicle could meet these demands [6].

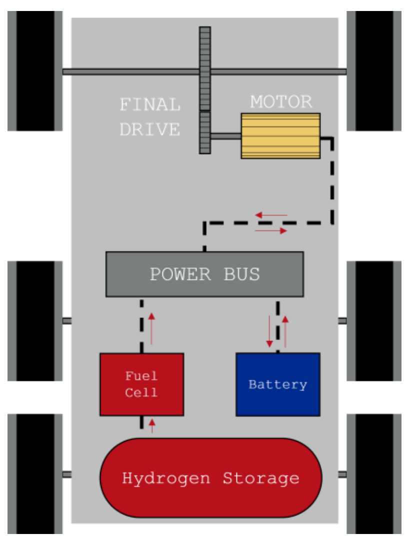


Introduced in the previous section, there are many benefits of hydrogen fuel cells over other technologies for semi-truck applications. It has better efficiency, range, less downtime for fueling, is more environmentally friendly, and can withstand a high payload. Due to these benefits, we believed a hydrogen fuel cell hybrid electric vehicle architecture met the needs of the semi-truck industry while addressing the problem of climate change.

Once we found our problem and our solution to that problem, we had to figure out how all the components were going to be tied together. We developed an architecture for our specific application. With so many different hybrid architectures that have been developed there were a lot of inspirations. The Toyota Mirai is a notable example of this. Since around 2014 it has been pushing the envelope in the fuel cell space. Then there was a project from a previous AUTO566 semester that developed a Fuel Cell Ultracapacitor Battery Hybrid Vehicle configuration where there was a motor, fuel cell, battery, and ultracapacitor electrically connected to a power bus [20]. There were plenty of other examples that were inspirations to our architecture. Defining the power flow for the vehicle helped us narrow in on a final vehicle architecture:

1. **Fuel cell alone propelling:** the electronic interface isolates the battery from the power line and fuel cell pack alone supplies power to the electric motor.
2. **Battery alone propelling:** the fuel cell pack is isolated from the power line and the battery alone supplies power to the electric motor.
3. **Hybrid propelling:** both the fuel cell system and battery provide power to the electric motor simultaneously.
4. **Fuel cell power split mode:** the fuel cell power is split into two parts by the electronic interface. One part is used to power the electric motor and the other charges the battery.
5. **Regenerative braking:** the electric motor functions as a generator to recover the braking energy and stores it in the battery.

From there, the architecture began to take shape. There is the fuel cell and battery connected electrically to the power bus, supplying power to the electric motor, individually or simultaneously. As mentioned above, the fuel cell can be used to charge the battery. The motor is electrically connected to the power bus and used to drive the final drive. The electric motor also begins the regenerative braking process with a maximum power of 480 [kW]. Then there is the final drive which allows the maximum driving speed of 85 miles per hour for the vehicle.



Vehicle Modeling and Integration

2.1 Vehicle Parameters

Weight

A class 8 semi-truck derives its name from the maximum gross vehicle weight which is allowed for a semi-truck: 80,000 [lbs.]. To ensure that our vehicle would meet the needs of all potential customers we utilized the maximum possible vehicle weight for this class of vehicle in our model. A compilation of semi-truck weights from the Federal Highway Administration was also analyzed and it was determined that 90% of vehicles typically operate at weights under 73,000 [lbs.] [30]. This figure can be used to help gain a more complete picture of the expected vehicle loads for the application and the performance of the powertrain.

Aerodynamic Drag

The aero dynamic drag coefficient and front area for a standard semi-truck was utilized from a model created by Air Shaper, a computational fluid dynamics software company, which performed a comparison between a conventional semi-truck and the recently announced Tesla semi-truck. Air Shaper's analysis resulted in a C_d equal to 0.43 for a conventional semi-truck and a frontal area, A_f, of 9.92 [m^2] [28]. These values would be used to determine the load on the vehicle due to aero dynamic drag.

Wheel Radius

The wheel radius is an important value in the vehicle model to determine both the rolling resistance and the final drive ratio. A standard semi-truck tire model was chosen for our applications: the 295/75R22.5 [29]. This model number corresponds to the following parameters of the tire:

Nominal Section Width in [mm]	295
Nominal Aspect Ratio	75
Nominal Rim Diameter	22.5
Nominal Rim Radius	285.75

From these values we can determine the tire radius, R_w, to be 0.507 [m]. The extended calculations can be found in the MATLAB implementation of the vehicle model.

Final Drive Ratio

With an accurate tire radius determined we could calculate an appropriate final drive ratio for the class 8 semi-truck. This calculation begins by determining the maximum velocity for the vehicle. The Daily Average vs. Maximum Driving Speed provides a reasonable maximum driving speed of ~75 [mph] to which we add a buffer of 10 [mph] to ensure we can meet the demands of the customers. This results in a maximum driving speed of 85 [mph]. With a maximum velocity determined a series of conversion occurs to translate that value into the expected motor rotational velocity. These calculations can be found in the MATLAB implementation of the vehicle mode and result in a final drive ratio, F_d, of 8.38.

Vehicle Load

The load on the vehicle is modeled as a composite of three diverse sources: the grade, aero dynamic drag, and rolling resistance. These three sources are integrated into the Simulink vehicle model using the three equations below and the parameters discussed above:

$$F_{grade} = \sin\left(\theta \frac{\pi}{180}\right) M_v \, g$$

$$F_{aero} = C_d \frac{\rho \, v^2}{2} A_f$$

$$F_{rolling} = M_v \, g \, f_{rolling} \, R_w$$

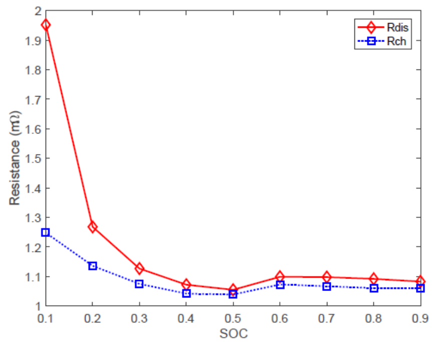
2.2 Battery

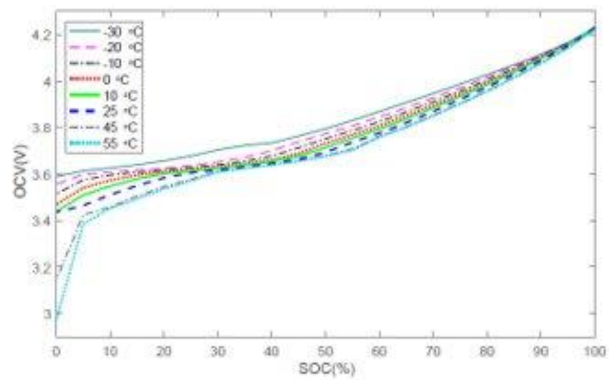
After investigating the batteries used for automotive applications, the batteries of Nickel Manganese Cobalt Oxide (NMC) Lithium-ion are a good option for our Class 8 truck application. They are currently available in the market, high capacity and performs better under a wider range of temperatures, specifically at low temperatures (-20 °C). Some of their limitations comes from the supply chain which relies on the mining scarce metals like cobalt and nickel from countries with unstable governments and have questionable mining practices like child labor and slavery. This is pushing investigations on batteries cobalt and nickel free. But for the purpose of this study and application NMC Li-ion batteries are going to be used.

The parameters input in the truck model comes from the article Study on the Characteristics of a High-Capacity Nickel Manganese Cobalt Oxide (NMC) Lithium-Ion Battery—An Experimental Investigation. The main characteristics of the cell are shown in the table below [44]:

Item	Specification Parameter
Battery Dimension	L/mm: 148.40 ± 0.30 W/mm: 39.70 ± 0.30 H/mm: 95.00 ± 0.30
Nominal Capacity	76.5 Ah (1/3 C) 75.0 Ah (1 C)
Nominal Voltage	3.70 V (1/3 C) 3.65 V (1 C)
Weight Internal Impedance Internal Resistance Upper Charge Cut-Off Voltage	1.32 kg 0.65 mΩ @50% SOC, 1 kHz 1.3 mΩ @10 s 200 A, 50% SOC 4.25 V
Lower Discharge Cut-Off Voltage	2.80 V ($T > -10$ °C) 2.50 V (-20 °C $\leq T \leq -10$ °C) 2.10 V ($T \leq -20$°C)
Continuous Charging Current	75 A (25 °C)
Continuous Discharge Current	75 A (25 °C)
Maximum Pulse Charging Current Maximum Pulse Discharge Current Charge Upper Limit Protection Voltage Charge Lower Limit Protection Voltage	350 A @10 s, 50% SOC, 25 °C 350 A @10 s, 50% SOC, 25 °C 4.30 V 2.5 V (25 °C)
Working Temperature	Discharge temperature range: −30~55 °C Charge temperature range: −20~55 °C

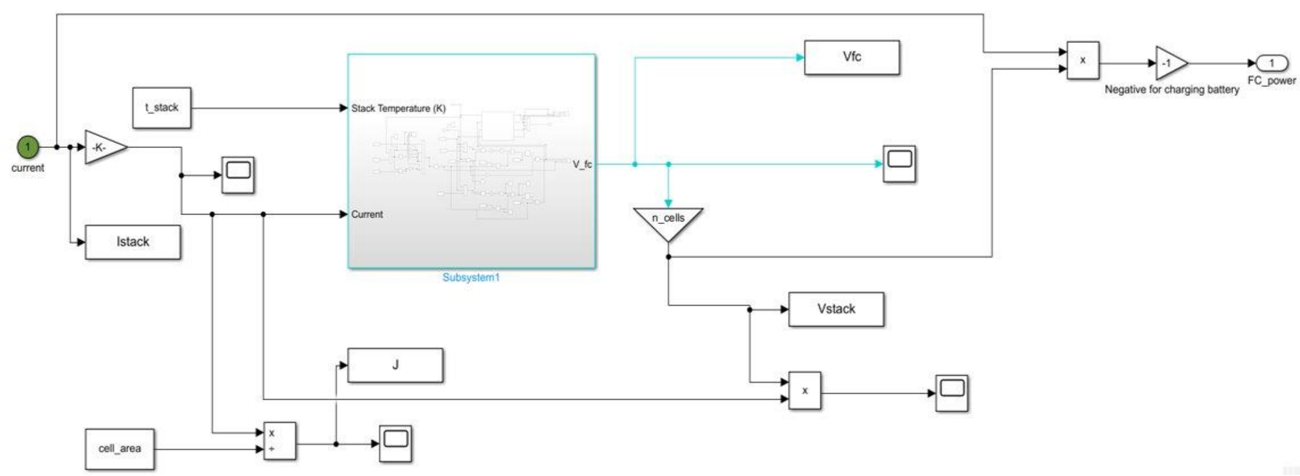
Also, internal resistance was available in the article as shown in the figure below [44]:





2.3 Fuel Cell Model

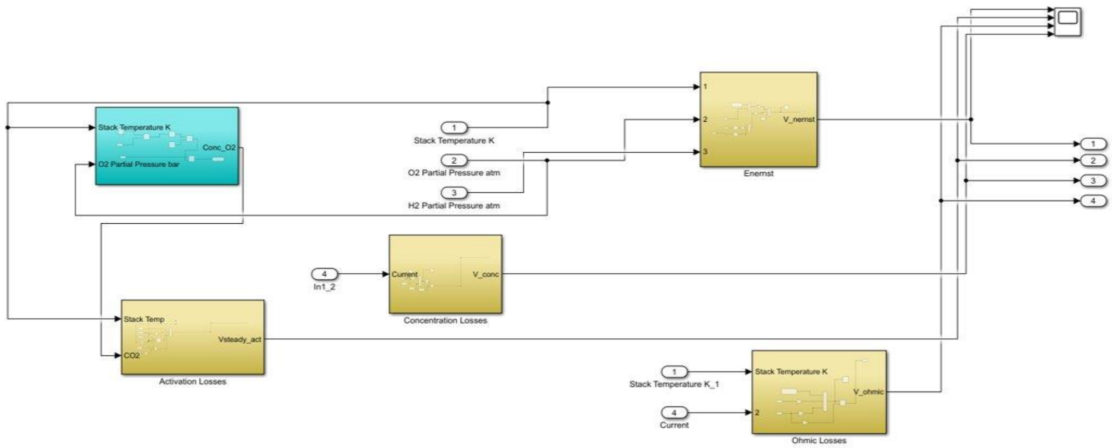
For fuel cells the analysis was set up using the Toyota Mirai fuel cell stack as the benchmark. The PEMFC (Proton Exchange Membrane fuel cell) was modeled based on a research paper which uses a Horizon H-500 fuel cell for the model [45]. A static model was developed in Simulink to meet the power demand of the vehicle.



The ideal voltage of the fuel cell is obtained from the Nernst equation corresponding to the Hydrogen Fuel Cell. The value of the open circuit voltage at Equilibrium was obtained as 1.23 [V].

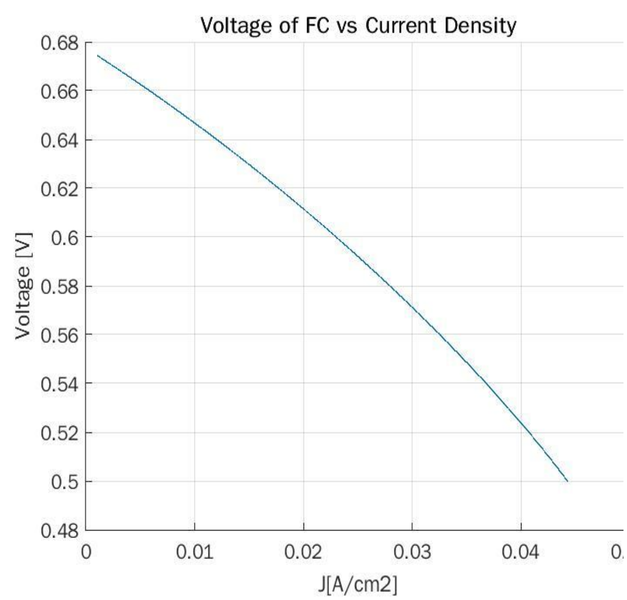
The concentration of oxygen was modeled using the Partial pressures of Hydrogen and Oxygen at Cathode and Anode, respectively. This concentration was used in the calculation of the steady-state activation losses. The steady-state activation losses correspond to the kinetic losses in the fuel cell (slow rate of reaction at electrode surfaces). The ohmic losses were this accounting for the internal resistance of the cell. Lastly, we have concentration losses or also termed Mass transport losses account for the reduced concentration of reactants as the fuel is consumed. This means that the concentration losses are effective at high current densities. The

Fuel cell Simulink model for the calculation of internal voltage losses has been attached for reference.

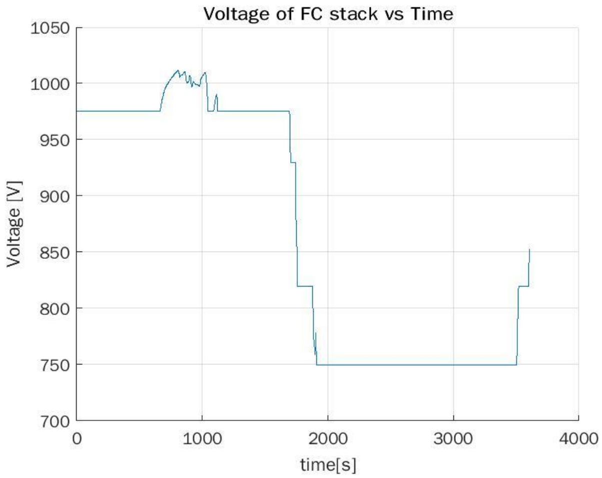


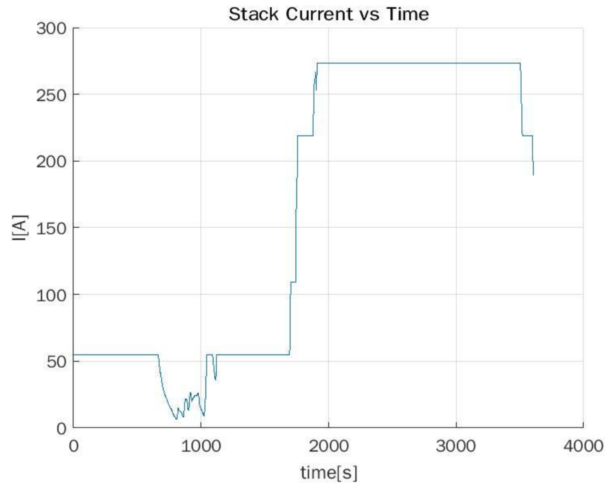
The final set of fuel cell parameters obtained on scaling the single PEMFC model to the Wolverine prototype is mentioned in the table below. The polarization curve obtained for the steady state PEMFC model is shown below. The graph does not resemble the typical polarization curve of a dynamic model of a fuel cell model because the thermodynamic profile of the fuel cell system has not been integrated into the model.

DESIGN PARAMETERS	VALUE
FUEL CELL STACK POWER[KW]	300
STACK CURRENT(A)	312
NUMBER OF STACKS	13
CURRENT PER STACK(A)	24
VOLTAGE OF FUEL CELL STACK(V)	970
NUMBER OF FUEL CELLS	1500
VOLTAGE OF SINGLE FUEL CELL(V)	0.645
CELL AREA (in cm2)	475
STACK TEMPERATURE (IN K)	305



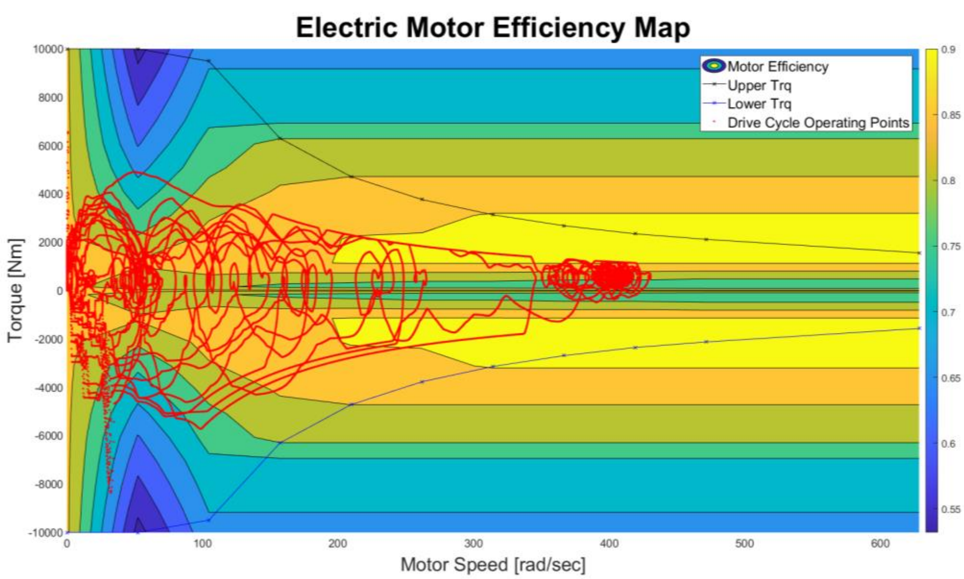
The graphs of Fuel cell stack current and stack voltage with respect to time of the model when a composite load cycle was used to run the vehicle model is depicted below. We can observe that the fuel cell is able to meet the requested Fuel cell power request demand from the vehicle model.





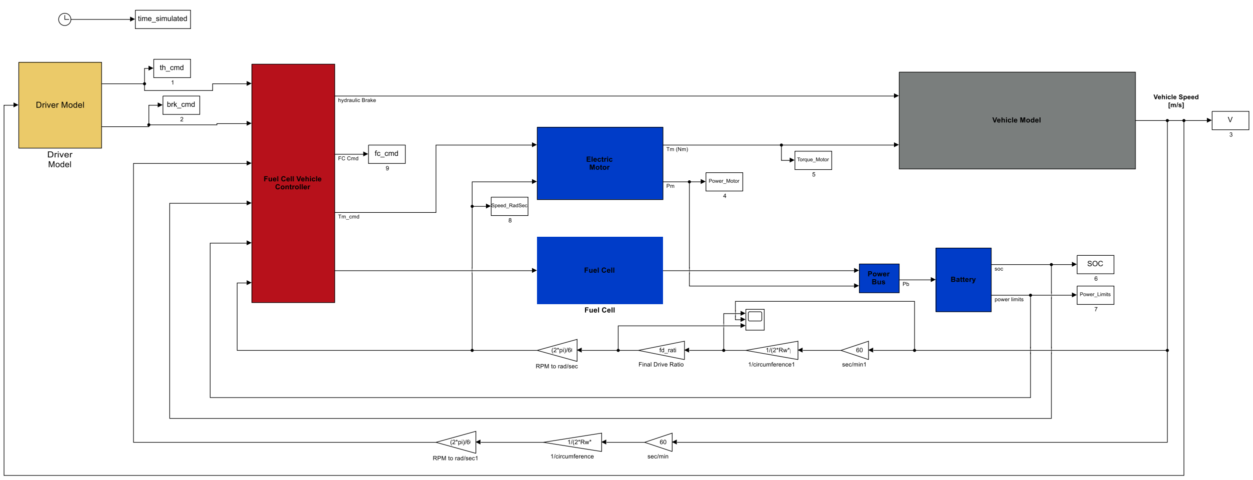
2.4 Electric Motor

The electric motor parameters utilized in our model were derived from the motor parameters used in the Prius model. This decision assumes that the electric motor efficiency table for the Toyota Prius is representative of similarly constructed electric motors consisting of an increased number of windings to accommodate higher torque demands. The minimum and maximum motor speeds were maintained at 0 [RPM] and 6000 [RPM] respectively while the maximum torque for the motor was scaled to 10,000 [Nm]. This maximum torque value was chosen so that most of our operating points during the CARB HHDDT Compositive Drive Cycle would remain in an area of high motor efficiency while still allowing for torque head room during at grade vehicle operations. The motor efficiency map can be seen below with the points of motor operation depicted in red.



2.5 Simulink Integration

Each of the above components; vehicle parameters, battery, fuel cell, and electric motor, were integrated into a modified version of the Prius THS Simulink model. The modifications included simplifications to the vehicle model which removed the planetary gear set and a shift in the controls block from a dual electric motor and engine design to a design consisting of a controller for a single electric motor and the ECMS control block to determine the power demand for the fuel cell. The model is implemented with a vehicle weight of 80,000 [lbs.] (36287.39 [kg]) to ensure that our vehicle can meet the demands of the market sector. The model is also run on a flat road, road grade equal to 0, which opens opportunities for future work analyzing performance in mountain assents and descents which have implications for maximum power demand while traveling up and regenerative breaking overloading the battery when traveling down.



2.6 Controls and Optimization

The control strategy for a fuel cell electric vehicle is much more straight forward than for a similar hybrid vehicle utilizing an internal combustion engine and a combination of electric motors connected through a series of planetary gear sets. This is due to the monotonic nature of the fuel cell efficiency compared to an internal combustion engine. In the case of an ICE, electric motors are used to supplement the vehicle power demand to allow the ICE to remain in a region of high efficiency. Conversely the fuel cell has a much smaller difference in efficiency characteristics across its range of operation, with improvements seen in lower regions of power demand, and is not concerned with a mechanical coupling to the drivetrain which ties an ICE operation directly to that of the vehicle speed. With this decoupling between our electrical systems and mechanical systems our control strategy can focus on “babying the battery” through a charge depleting / charge sustaining methodology.

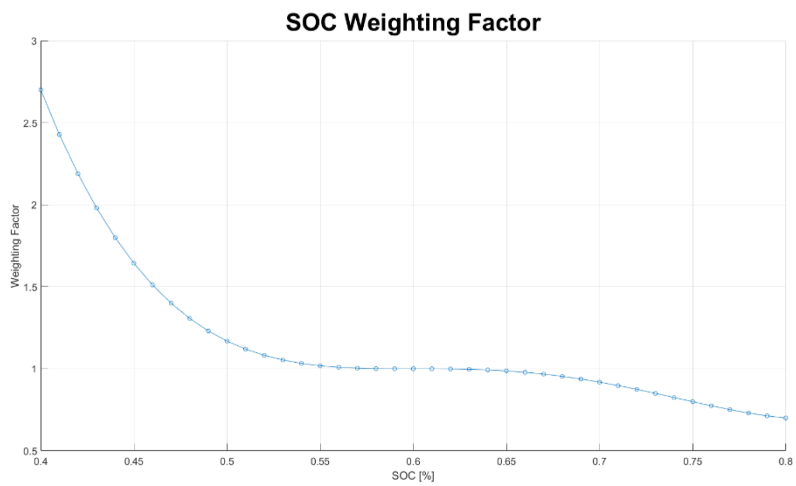
To achieve a charge depleting / charge sustaining control algorithm we implemented Equivalent Consumption Minimization Strategy (ECMS) which utilizes an equivalency factor to create a comparative heuristic between the power consumptions for the battery and the fuel cell. This equivalency factor is then paired with an SOC Weighting Factor which penalizes battery usage at lower SOCs prompting an increased power output from the battery. Both the equivalency factor and weighting factor were utilized from AUTO566 Homework 4. The constraints and minimization equations for the ECMS algorithm are illustrated in the following equations [40]:

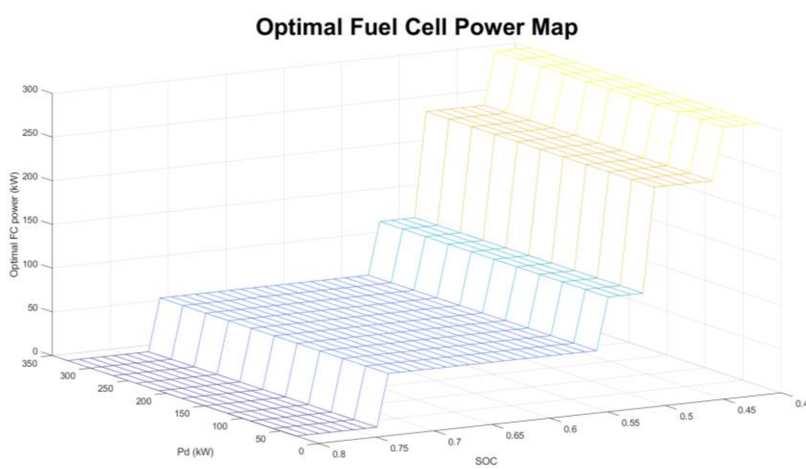
At time t:

$$J_t = J_t(P_{FC}(t), P_{em}(t))$$

$$\{P_{FC}^{opt}(t), P_{em}^{opt}(t)\} = argmin_{\{P_{FC}^{opt}(t), P_{em}^{opt}(t)\}}(J_t)$$

$$subject\ to \begin{cases} P_{req}(t) = P_{FC}(t) + P_{em}(t) \\ SOC_{min} < SOC(t) < SOC_{max}\ \ \forall t \\ 0 \leq P_{FC}(t) \leq P_{FC,max}(t) \\ P_{em,min}(t) \leq P_{em}(t) \leq P_{em,max}(t) \end{cases}$$



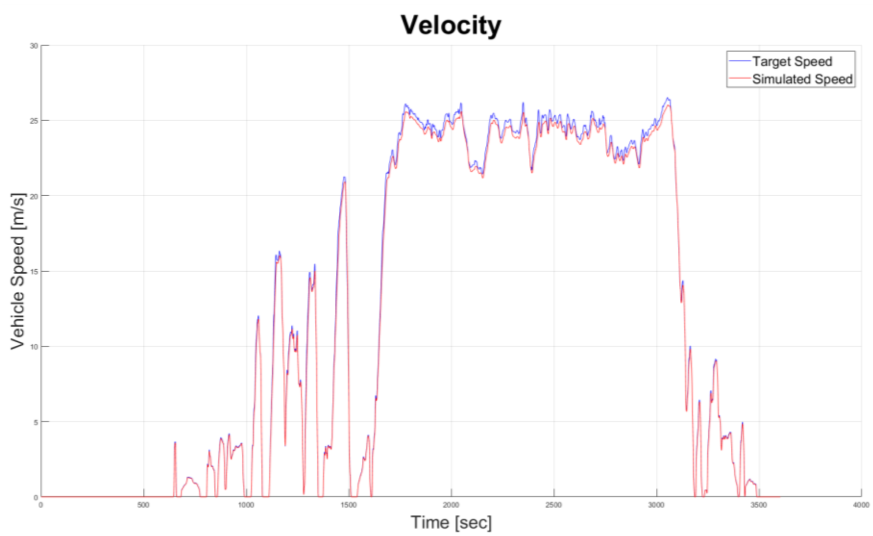


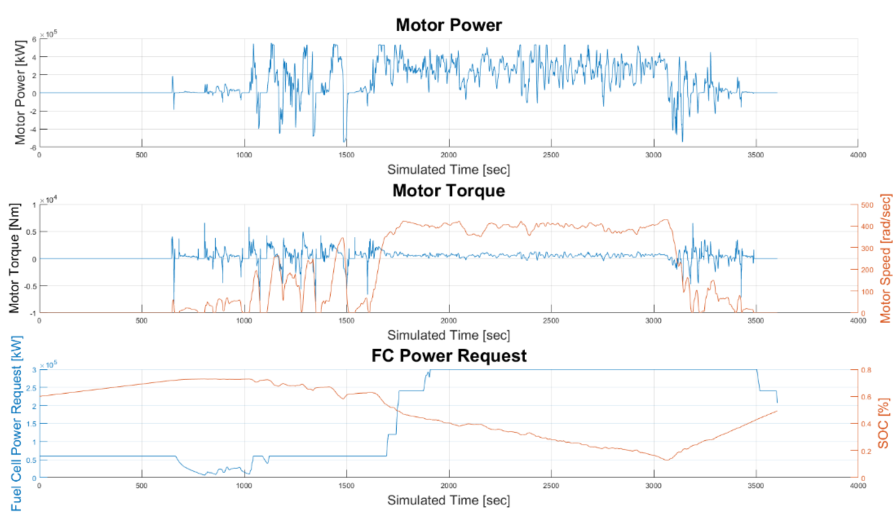
Results

Following the model integration and troubleshooting the team was able to achieve a mean error of 0.20 [m/s] and a maximum error of 1.74 [m/s] for the CARB Heavy Heavy-Duty Diesel Truck Composite Cycle. These results reinforced the scaling and design decisions that were made throughout the vehicle modeling phase of the project. The vehicle achieved an energy consumption per mi of 4.96 [kWh/mi] which translates to 0.165 [kg of hydrogen/mi]. These values are more closely aligned to those of the diesel vehicles in our competition than the electric vehicles. This suggests that there may still be opportunities in the implementation of the regenerative breaking algorithm or that the reported efficiency of the prototype fuel cell electric semi-trucks and fully electric semi-trucks were conducted under different operating conditions or with more optimistic numbers than we achieved in our model.

kWh/mi	kg hydrogen/mi
4.96	0.165

Table 2 Resulting energy and hydrogen consumption of the Wolverine.





Future Work

For future work it is recommended to change the static fuel cell model to a dynamic fuel cell model which is derived from hydrogen and oxygen flow management also considers thermal effects and adjust parameters, especially current density [A/cm^2] since lowering current density is particularly good for extending the durability of the fuel cell. But it is not good for efficiency and energy density. Another adjustment will be to increase the cell voltage from 6.8 to 7.65 [V]. since this small increment in the voltage current is a step forward on establishing a balance between power density and durability [41].

After updating the fuel cell model the electric motor efficiency map can be updated also with a continued refinement of the control strategy to improve the overall vehicle efficiency from 4.9 [kWh/mi]. While this value places our vehicle in a competitive region compared to diesel semi-trucks it is still behind those or BEV vehicles which have reported efficiencies of 2 [kWh/mi].

Conclusion

Greenhouse gas emissions have had a negative impact on the environment which has in turn affected various industries. Transportation is amongst the highest impacted and it is projected to continue to rise. Technologies that produce clean energy, such as fuel cells, will help reduce the impact of semi-truck and transportation on the environment.

Aside from environmental benefits, we had to figure out what fuel cell technology means for the transportation industry. Due to the frequency and length of travel there was a need for vehicles to have the ability to travel long distances. Class 8 semi-trucks should be able to carry large payloads while having a total weight of up to 80,000 [lbs.]. They also must be able to maintain speed and power while carrying that large amount of weight. Reviewing data from sources, such as the National Renewable Energy Laboratory (NREL), we are confident that a hydrogen fuel cell HEV presents an opportunity to capitalize in the semi-truck space.

Implementing fuel cell technology in class 8 semi-trucks still allows the vehicle to travel at long range and carry heavy payloads as well as recharge at a faster rate. It recharges faster than battery electric vehicles and, due to the high energy density, it overcomes any range or weight carrying challenges that battery electric vehicles face as well. Discovering these benefits made it simple to move forward with our approach to the project.

After implementing and simulating our fuel cell vehicle architecture into the model with assistance from other benchmarking models, and then developing a control and optimization plan using what was learned in class, we found key results that helped us see where we measured up to the competition. Below is the table found in the competition section but with our fuel cell hybrid electric class 8 semi-truck known as the Wolverine.

	Wolverine	Diesel	Nikola Tre BEV	Nikola Tre FCEV	ACS Energy Optimal FCEV	Tesla Semi	Mercedes-Benz GenH2 Truck
Range [mi]	-	1000	350	500	600	600	620

Payloads [lbs.]	48,000	62,000	-	-	53,000	-	48,000
Maximum Speed [mph]	85	85	75	-	-	60	75
Energy Consumption [kWh/mi]	4.96	4.45 - 6.3	-	-	1.9	2	-
Power [kW]	480	350 – 500	480	480	-	745	400
Recharge Time [min]	-	20	120 (10-80% SOC)	20	-	30 (80% SOC)	20

Table 3 Competitive analysis between the Wolverine and diesel, battery electric, and fuel cell electric class 8 semi-trucks [15][26][27][28][29][30].

We assumed parity for payload with the Mercedes-Benz GenH2 semi-truck. As described earlier in the report we found our final drive ratio thus giving us an 85 [mph] maximum speed. The key metrics that were developed from our model were an energy consumption of 4.96 [kWh/mi], a hydrogen consumption of 0.165 [kg/mi], and total power of 480 [kW]. While the energy consumption turned out to be higher than that of the Tesla Semi our vehicle still achieved a competitive result in the marketplace and has opportunities for future improvement. Overall, the Wolverine measured up well against a diverse competitive group and offers a road map for reducing the emissions of the trucking industry.

References

[1] Bill Gates. (2021) How to fight climate change and avoid a climate disaster p. 75

[2] Www, T., & Org. (2018). Beyond road vehicles: Survey of zero-emission technology options across the transport sector. https://theicct.org/sites/default/files/publications/Beyond_Road_ZEV_Working_Paper_20180718.pdf

[3] Drew Kodjak. 7 May 2021, 09:36. A strategy to decarbonize the global transport sector by 2050, explained. https://theicct.org/blog/staff/vision2050-explained-may2021

[4] Davis, S. C. Transportation Energy Data Book. Edition 37; Oak Ridge, TN: Oak Ridge National Laboratory 2018. Retrieved from: http://cta.ornl.gov/data, 2018.

[5] Hooper, A.; Murray, D. An Analysis of the Operational Costs of Trucking: 2017 Update; 2017; Technical Report, American Transportation Research Institute, Arlington, VA, USA.

[6] Kevin Walkowicz, Adam Duran, Evan Burton. 8/1/2014. Fleet DNA Project Data Summary Report NREL (National Renewable Energy Laboratory) Fleet DNA Project Data Summary Report for Class 8 Tractors (nrel.gov)

[7] Venkatasubramanian Viswanathan, July 3, 2017. Performance Metrics Required of Next-Generation Batteries to Make Practical Electric Semi Truck. https://www.researchgate.net/publication/317966352_Performance_Metrics_Required_of_Next-Generation_Batteries_to_Make_a_Practical_Electric_Semi_Truck

[8] Fact #620: April 26, 2010 Class 8 Truck Tractor Weight by Component. https://www.energy.gov/eere/vehicles/fact-620-april-26-2010-class-8-truck-tractor-weight-component

[9] Shashank Sripad, and Venkatasubramanian Viswanathan, 04 Dec 2018, Quantifying the Economic Case for Electric Semi-Trucks. Page 3. http://pubs.acs.org

[10] Daimler, May 19, 2021, Fuel-cell truck Start of testing of the new GenH2 Truck prototype, https://www.daimler.com/innovation/drive-systems/hydrogen/start-of-testing-genh2-truck-prototype.html

[11] Hengbing Zhao, Andrew Burke, Lin Zhu, November 17-20, 2013, Analysis of Class 8 Hybrid-Electric Truck Technologies Using Diesel, LNG, Electricity, and Hydrogen, as the Fuel for Various Applications. Table 1. https://www.evs27.org/download.php?f=papers/EVS27-6490424.pdf

[12] Jason Marcinkoski, 1 Ram Vijayagopal, 2 Jesse Adams, 1 Brian James, 3 John Kopasz, 2 Rajesh Ahluwalia2, 10/31/2019. DOE Advanced Truck Technologies Subsection of the Electrified

Powertrain Roadmap Technical Targets for Hydrogen-Fueled Long-Haul Tractor-Trailer Trucks. Table 12. Simple Cost of Ownership Estimate.
https://www.hydrogen.energy.gov/pdfs/19006_hydrogen_class8_long_haul_truck_targets.pdf

[13] Transport and Environment, June 2020, Comparison of hydrogen and battery electric trucks,
https://www.transportenvironment.org/wp-content/uploads/2021/07/2020_06_TE_comparison_hydrogen_battery_electric_trucks_methodology.pdf

[14] Nikola, 2021, Nikola TREBEV, Nikola motor, https://nikolamotor.com/tre-bev

[15] Sripad, S., & Viswanathan, V. (2017). *Performance Metrics Required of Next-Generation Batteries to Make a Practical Electric Semi Truck.* ACS Energy Letters, 2(7), 1669–1673. https://doi.org/10.1021/acsenergylett.7b00432

[16] Desantes, J. M., Novella, R., Pla, B., & Lopez-Juarez, M. (2021). *Impact of fuel cell range extender powertrain design on greenhouse gases and NOX emissions in automotive applications.* Applied Energy, 302, 117526. https://doi.org/10.1016/j.apenergy.2021.117526

[17] Sorlei, I.-S., Bizon, N., Thounthong, P., Varlam, M., Carcadea, E., Culcer, M., Iliescu, M., & Raceanu, M. (2021). *Fuel Cell Electric Vehicles—A Brief Review of Current Topologies and Energy Management Strategies. Energies*, 14(1), 252. https://doi.org/10.3390/en14010252

[18] *Fuel Cells.* (2015).
https://www.energy.gov/sites/prod/files/2015/11/f27/fcto_fuel_cells_fact_sheet.pdf

[19] O'hayre, R. P., Suk-Won Cha, Colella, W. G., & Prinz, F. B. (2016). *Fuel cell fundamentals.* John Wiley & Sons Inc.

[20] Kim, Y., & Smith, W. (2010). *Optimal Control and Design of a Fuel Cell-Ultracapacitor-Battery Hybrid Vehicle* (pp. 1–22) [Review of Optimal Control and Design of a Fuel Cell-Ultracapacitor-Battery Hybrid Vehicle].

[21] Spiegel, C. (2008). *PEM fuel cell modeling and simulation using Matlab.* Academic Press/Elsevier.

[22] G. Wu, et al., *Powertrain architectures of electrified vehicles: Review, classification and comparison*, Journal of the Franklin Institute. (2014), http://dx.doi.org/10.1016/j.jfranklin.2014.04.018

[23] Liu, J., Anwar, M., Chiang, P., Hawkins, S. et al., *Design of the Chevrolet Bolt EV Propulsion System*, SAE Int. J. Alt. Power. 5(1):2016, doi:10.4271/2016-01-1153.

[24] Khan, A., Grewe, T., Liu, J., Anwar, M. et al., *The GM RWD PHEV Propulsion System for the Cadillac CT6 Luxury Sedan*, SAE Technical Paper 2016-01-1159, 2016, doi:10.4271/2016-01-1159.

[25] Walkowicz, K., Duran, A., & Burton, E. (n.d.). *Fleet DNA Project Data Summary Report*. Retrieved December 4, 2021, from https://www.nrel.gov/transportation/assets/pdfs/fleet_dna_class_8_tractors_report.pdf

[26] Nikola Tre: Battery-Electric Daycab Semi-Truck. (n.d.). Nikola Motor Company. Retrieved December 9, 2021, from https://nikolamotor.com/tre-bev

[27] Nikola Tre: Fuel-Cell Electric Day cab Semi-Truck. (n.d.). Nikola Motor Company. Retrieved December 9, 2021, from https://nikolamotor.com/tre-fcev

[28] *Nikola Two: Fuel-Cell Electric Sleeper Semi-Truck*. (n.d.). Nikola Motor Company. Retrieved December 4, 2021, from https://nikolamotor.com/two-fcev

[29] Tesla. (2019). *Tesla Semi*. Tesla Semi. https://www.tesla.com/semi

[30] *Daimler Presents GenH2 Truck Fuel-Cell Concept Truck*. (n.d.). InsideEVs. Retrieved December 4, 2021, from https://insideevs.com/news/444480/mercedes-genh2-truck-fuel-cell-concept-truck/

[31] Stefanopoulou, A.S. (2021), Siegel, J.S. (2021), *Introduction-Overview to PEM Fuel Cells* (1-19), College of Engineering, University of Michigan, https://umich.instructure.com/courses/478683/files/folder/Lecture%20slides?preview=23118508

[32] Fuel Cell Electric Vehicles 2022-2042. (2021). In www.idtechex.com. https://www.idtechex.com/en/research-report/fuel-cell-electric-vehicles-2022-2042/844

[33] Tesla Semi Truck - Aerodynamics analyzed. (2018, September 12). Air Shaper. https://airshaper.com/cases/tesla-semi-truck-aerodynamics-analyzed

[34] Truck. (n.d.). TAWAS TIRES. Retrieved December 10, 2021, from http://tawastires.com/pf/truck/

[35] Distribution of Class 8 Trucks by On-Road Vehicle Weight, 2008. https://tedb.ornl.gov/wp-content/uploads/2019/04/Figure5_06.xlsx

[36] Modeling and Simulation of a Proton Exchange Membrane Fuel Cell Alongside a Waste Heat Recovery System Based on the Organic Rankine Cycle in MATLAB/SIMULINK Environment https://www.mdpi.com/2071-1050/13/3/1218

[37] FUEL CELL SECTION
https://www.energy.gov/sites/default/files/2017/05/f34/fcto_myrdd_fuel_cells.pdf

[38] Horizon Fuel Cell Technologies. 2013. Available online: https://www.horizonfuelcell.com/ (Accessed on 12 November 2021)

[39] Open-Source Dynamic Matlab/Simulink 1D Proton Exchange Membrane Fuel Cell Model https://www.mdpi.com/1996-1073/12/18/3478

[40] A-ECMS: An Adaptive Algorithm for Hybrid Electric Vehicle Energy Management, European Journal of Control, Volume 11, Issues 4–5, 2005, Cristian Musardo, Giorgio Rizzoni, Yann Guezennec, Benedetto Staccia.

[41] David A. Cullen 1, K. C. Neyerlin 2, Rajesh K. Ahluwalia3, Rangachary Mukundan4, Karren L. More 1, Rodney L. Borup 4, Adam Z. Weber 5, Deborah J. Myers6 and Ahmet Kusoglu 5. 2021. New roads and challenges for fuel cells in heavy-duty transportation. https://doi.org/10.1038/s41560-021-00775-z

[42] Drive Cycle Analysis Tool – DriveCAT. NREL.gov (n.d.).
https://www.nrel.gov/transportation/drive-cycle-tool/

[43] Saurabh Tembhurne, Fredy Nandjou and Sophia Haussener, Nature Energy | VOL 4 | MAY 2019, A thermally synergistic photo-electrochemical hydrogen generator operating under concentrated solar irradiation. https://doi.org/10.1038/s41560-019-0373-7

[44] Ruifeng Zhang 1,2, * ID, Bizhong Xia 1, Baohua Li 1, Yongzhi Lai 2, Weiwei Zheng 2, Huawen Wang 2, Wei Wang 2 and Mingwang Wang 2. Energies 2018, 11, 2275. 29 August 2018. Study on the Characteristics of a High-Capacity Nickel Manganese Cobalt Oxide (NMC) Lithium-Ion Battery—An Experimental Investigation. https://www.mdpi.com/1996-1073/11/9/2275

[45] Sharjeel Ashraf Ansari 1, Mustafa Khalid 1, Khurram Kamal 1, Tahir Abdul Hussain Ratlamwala 1, Ghulam Hussain 2 and Mohammed Alkahtani 3. Sustainability 2021.25 January 2021. Modeling and Simulation of a Proton Exchange Membrane Fuel Cell Alongside a Waste Heat Recovery System Based on the Organic Rankine Cycle in MATLAB/SIMULINK Environment. https://www.mdpi.com/2071-1050/13/3/1218